6th WORLD LANDSLIDE FORUM
2023 FLORENCE ITALY
14-17 NOVEMBER 2023

LANDSLIDE SCIENCE FOR SUSTAINABLE DEVELOPMENT

Proceedings of the 6th World Landslide Forum. Florence Italy, 14-17 November 2023
Abstract book

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INTRODUCTION

The 6th World Landslide Forum was held in Florence from November 14 and 17, 2023.

The World Landslide Forums are organized every three years to bring together scientists, engineers, practitioners, businesses, and policy makers, from around the world to share progress on landslide risk reduction on a global scale.

The 6th World Landslide Forum is jointly organized by the International Consortium on Landslides and the UNESCO Chair on Prevention and Sustainable Management of Geo-hydrological Hazards at the University of Florence, under the International Programme on Landslides (IPL) supported by five United Nations' organizations (UNESCO, WMO, FAO, UNDRR, UNU) and four international scientific organizations (ISC, WFEO, IUGS e IUGG).

The 6th World Landslide Forum was awarded the Medal of the President of the Italian Republic, which is given to events of great scientific and cultural importance.

More than 1100 participants from more than 60 countries attended the general plenary sessions, parallel scientific sessions, technical exhibitions, workshops and other side events during the four days of the Forum.

The Forum is entitled Landslide Science for Sustainable Development and contributes to the Sendai Framework for Disaster Risk Reduction, through the Kyoto Commitment for Landslide Risk Reduction which was signed by 90 institutions in 2020.

The aim of the Forum is to create a common platform to promote cooperation between all stakeholders involved in landslide risk reduction. This objective is particularly important considering that the Forum is taking place on the 60th anniversary of the Vajont landslide, the largest landslide disaster in Italy, which claimed more than 1900 lives.

The city of Florence was the cradle of the Renaissance of Arts and Science and is still today a cutting-edge city of science, culture, hospitality, and beauty. Florence has also been hit by severe natural disasters in the past, such as floods and landslides, which have caused enormous damage to its artistic and cultural heritage. We therefore consider Florence an ideal place to discuss the latest advances in research, technology, and policies for risk mitigation.

The General Conference on Landslide Risk Reduction, at the Opening Plenary Session on November 14, addressed the latest strategies of the landslide community to help achieve the global targets of the Sendai Framework for Disaster Risk Reduction. The High-Level Panel Discussion on the same day adopted the Florence Declaration on Landslide Risk Reduction, to share information and best practices, support research and development of new technologies, and build capacity at all levels to improve landslide preparedness and response.

Scientific plenary lectures were given by renowned scientists from four continents: Prof. Giovanni Battista Crosta from the University of Milan Bicocca, Prof. Xuanmei Fan from Chengdu University of Technology in China, Dr. Jonathan Godt from the United States Geological Survey and Prof. Olivier Dewitte from the Royal Museum for Central Africa.

The scientific program includes six main themes:

1. Kyoto Landslide commitment for sustainable development
2. Remote sensing, monitoring and early warning
3. Testing, modeling and mitigation techniques
4. Mapping, hazard, risk assessment and management
5. Climate change, extreme weather conditions, earthquakes and landslides
6. Progress in landslide science and applications

In the following days there were 47 parallel scientific sessions, with 853 scientific contributions, including 643 oral presentation and 210 posters.

In the Closing Plenary Session on November 17 the baton was passed to the 7th World Landslide Forum which will take place in Taipei in 2026.

We would like to thank all those who have contributed to the organization of the Forum over the past three years: especially the scientific committee, organizing committee, supporting organizations, partners, bodies that granted the patronage, and sponsors, for their contribution and strong commitment to the success of the 6th World Landslide Forum.

Nicola Casagli
WLF6 Chairman and ICL President

Veronica Tofani
WLF6 Secretary General and ICL Vice-President

14 NOVEMBER

15 NOVEMBER 2023

09:00-10:30 | AUDITORIUM

OPENING CEREMONY

Chairs: **Kyoji Sassa** - *ICL Secretary General*
Veronica Tofani - *ICL Vice President and WLF6 Secretary General*

09:00 Opening address from the primary organizers

Nicola Casagli - *ICL President and Chair of the 6th WLF*

Paolo Canuti - *UNESCO Chairholder prevention and sustainable mitigation of geo-hydrological hazard*

09:10 Greetings from United Nations organizations

Tshilidzi Marwala - *Under-Secretary-General of the United Nations / Rector of the United Nations University*

Mami Mizutori - *UN Special Representative of the Secretary-General for Disaster Risk Reduction*

Qu Dongyu - *Director-General of the Food and Agriculture Organization FAO*

Elena Manaenkova - *Deputy Secretary-General of the World Meteorological Organization WMO*

Lidia Brito - *Assistant Director-General for Natural Sciences of United Nations Educational, Scientific and Cultural Organization UNESCO*

09:35 Greetings from scientific organizations

Motoko Kotani - *Vice-President for Science and Society of the International Science Council ISC*

Mustafa B. Shehu - *President of the World Federation of Engineering Organizations WFEO*

John Ludden - *President of the International Union of Geological Sciences IUGS*

Chris Rizos - *President of the International Union of Geodesy and Geophysics IUGG*

09:55 Welcome messages from host organizations in Italy

Marco Pierini - *Vice Rector of Florence University*

Dario Nardella - *Major of Florence*

Eugenio Giani - *President of Tuscany Region*

Nello Musumeci - *Minister for Civil Protection*

Anna Maria Bernini - *Minister of University and Research*

Gilberto Pichetto Fratin - *Minister of Environment*

10:30 *Coffee break*

11:00-13:00 | AUDITORIUM
KLC2020 GENERAL CONFERENCE 2023 & HIGH-LEVEL PANEL DISCUSSION
Chair: **John Ludden** - *IUGS President*

11:00 Opening of the KLC2020 General Conference 2023
John Ludden - *IUGS President and Chair of KLC2020 General Conference* 2023

11:10 Signing ceremony of new KLC2020 signatories

Kyoji Sassa - *Secretary General of KLC2020*

Introduction of new KLC2020 partners:
Zhimin Wu - *Director, Forestry Division at FAO*
John Ludden - *President, International Union of Geological Sciences (IUGS)*
Fawu Wang - *Professor, Tongji University, China*
Jian Guo - *Professor, Tsinghua University, China*
Huiming Tang - *Vice-President, China University of Geosciences, China*
Rajendra Ratnoo - *Director, National Institute of Disaster Management (NIDM), India*
Kaoru Takara - *President, National Research Institute for Earth Science and Disaster Resilience (NIED), Japan*
Taichi Minamitani - *Director, Disaster Risk Reduction Team 1, Global Environment Department, Japan International Cooperation Agency (JICA), Japan*
Shinji Sassa - *Head, Soil Dynamics Group, National Institute of Maritime, Port and Aviation Technology, Japan*
Katsuo Sasahara - *Professor, Kochi University, Japan*
Ryosuke Seko - *Director, Chuo Kaihatu Cooperation, Japan*
Yoshiyuki Yagiura - *President, Kiso-Jiban Consultants Co., Ltd., Japan*
Julijana Bojadjieva - *Macedonian Association for Geotechnics, North Macedonia*
Jagath Gunatilake - *Director, Engineering Geology Research Group (EGRG), University of Peradeniya, Sri Lanka*
Jonathan Chambers - *United Kingdom Research and Innovation as represented by the British Geological Survey, UK*
Beena Ajmera - *Iowa State University, USA*

11:30 High-level panel discussion “KLC2020 Review and way forward”

Chairs: **Matjaž Mikoš** and **Qunli Han** - *Global Promotion Committee of IPL and KLC2020*

Panelists from KLC2020 partners:
- **Thomas Hofer** - *Senior Forestry Officer at FAO*
- **Yuki Matsuoka** - *Head UNDRR office in Japan*
- **Soichiro Yasukawa** - *Chief of Disaster Risk Reduction Unit at UNESCO*
- **Satoru Nishikawa** - *International Institute of Disaster Science*
- **Alexander Rudloff** - *Secretary General of IUGG*
- **Hiroshi Kitazato** - *Treasurer of IUGS*
- **Fabrizio Curcio** - *Department of Civil Protection Italian Government*
- **Stefano Laporta** - *ISPRA, Geological Survey of Italy*

Explanation of the Florence Declaration
Nicola Casagli - *ICL President and Chair of the 6th WLF*

12:45 Adoption of the Florence Declaration on Landslide Risk Reduction
John Ludden - *IUGS President and Chair of KLC2020 General Conference 2023*

12:50 Joint photo of the panelists and the new KLC2020 signatories

13:00 *Break*

14:00-16:00 | AUDITORIUM
WLF6 PLENARY LECTURES
Chairs: **Fausto Guzzetti** - *National Research Council* and **Vít Vilímek** - *ICL Vice-President*

14:00 Landslides in tropical environments: insight from the East African Rift
Olivier Dewitte - *Royal Museum for Central Africa*

14:30 Mechanisms and prediction of earthquake and climate change induced cascading hazards
Xuanmei Fan - *Chengdu University of Technology*

15:00 New US national strategy for landslide loss reduction
Jonathan Godt - *USGS*

15:30 Landslides impact on structures and infrastructures
Giovanni B. Crosta - *Università degli Studi di Milano Bicocca*

16:00 *Coffee break*

16:30-18:00 | AUDITORIUM
RECOGNITION AND AWARDS CEREMONY
Chairs: **Peter Bobrowsky** - *Chair IPL Awards Committee* and
Irasema Alcántara Ayala - *Chair IPL Evaluation Committee*

16:30 World Centers of Excellence on Landslide Risk Reduction

- Institute of Cold Regions Science and Engineering, Northeast Forestry University, China
- Croatian Landslide Group, Croatia
- Charles University, Czech Republic
- National Institute of Disaster Management (NIDM), India
- Amrita Vishwa Vidyapeetham, Amritapuri campus, India
- Universitas Gadjah Mada, Indonesia
- University of Calabria (UNICAL), Italy
- UNESCO Chair on Prevention and Sustainable Management of Geo-Hydrological Hazards, University of Florence, Italy
- CERI – Centre for Research on Prediction, Prevention, and Mitigation of Geological Risks, Italy
- Institute of Geography, National Autonomous University of Mexico (UNAM), Mexico
- JSC "Hydroproject Institute", Russia
- Laboratory of Engineering Geodynamics, Department of Engineering and Ecological Geology, Faculty of Geology, Moscow State University, Russia
- University of Belgrade, Faculty of Mining and Geology, Belgrade, Serbia
- University of Ljubljana -Faculty of Civil and Geodetic Engineering (UL FGG) and the UNESCO Chair on Water-related Disaster Risk Reduction (WR DRR), Ljubljana, Slovenia
- Engineering Geology Research Group (EGRG), Department of Geology, University of Peradeniya, Sri Lanka
- British Geological Survey, U.K.

17:00 Varnes Medals
Charles Ng - *Hong Kong University of Science and Technology* - 2022 Medal
Edward N. Bromhead - *formerly Kingston University UK* - 2022 Medal
Irasema Alcántara-Ayala - *National Autonomous University of Mexico* - 2023 Medal

17:30 IPL-KLC Award for Success

Maneesha V. Ramesh – 2021-2023 Award

17:40 Hiroshi Fukuoka IPL Award
Vít Vilímek and **Jan Klimeš** - *Charles University* - 2021-2023 Award

17:50 Oldrich Hungr Awards
Clarence Choi - *University of Hong Kong* - 2022 Award
Tommaso Carlà – *University of Florence* - 2023 Award

18:00-19:00 | AUDITORIUM
Welcome Cocktail

SESSION 2.7

INVESTIGATION OF MASS MOVEMENTS IN ALPINE ENVIROMENTS WITH REMOTE SENSING METHODS

REMOTE SENSING APPLICATIONS FOR DEFORMATION MONITORING AND PROCESS ANALYSES OF LANDSLIDES IN ALPINE ENVIRONMENT

Christine Fey[1], Rechberger Christina[1,2], Klaus Voit[1], Christian Zangerl[1]
[1]University of Natural Resources and Life Sciences, Institute of Applied Geology, Department of Civil Engineering and Natural Hazards, Vienna, Austria, [2]Disaster Competence Network Austria (DCNA), Vienna, Austria

Purpose: In mountain regions, changing boundary conditions from climate change such as melting glaciers, permafrost retreat, extreme precipitation events and sudden snowmelt influence the stability of alpine soil and rock slopes. Slope deformation processes are complex and a sound understanding is a prerequisite to investigate the impact of changing climatic conditions and to predict the future behaviour as well as to develop safety measures. Based on imagery and laser scanning data we exploit past and present landslide evolution of rock slides in the Eastern Alps. We used available laser scanning and imagery data from national, federal and local archives for North and South Tyrol and Trentino and applied UAV and TLS monitoring campaigns with the aim to i) analyse the retrospective landslide development over a long time period and ii) to analyse the current landslide behaviour by appropriate and ongoing monitoring methods.

Methods: In the frame of this study, four active deep-seated rock compound slides in the mountain of Austria and Italy were analysed. The study sites differ in their topography as well as process characteristics. For process and deformation analyses, the data from airborne and imaging campaigns was collected and field campaigns with terrestrial laser scanning and UAV were performed. The data from these different sources was pre-processed and compiled into a common coordinate reference system. Slope deformation processes with a destruction of the surface, e.g. due to rock fall, were analysed by means of a robust 3D distance measurement approach for point cloud data. Slope processes with en-block displacements (e.g. slides) were analysed by applying an image correlation and breakline tracking technique. The derived distance change and displacement maps, together with information from field surveys and terrestrial photographs, were used for interpretation.

Results: The applied methods allow i) the identification of different landslide processes (i.e. rock and soil slides, rock fall, rock avalanches, ii) the delineation of different slabs (rock slide) and analyses of their activity, geometry and kinematics and iii) the interpretation of the failure mechanism (e.g. toppling or rotational sliding). The analyses show that all rock slides are composed of different slabs with different spatial and temporal deformation behaviour. The extracted information was used to develop a geological model of the slope deformation. The information about kinematics and the geometry of the landslides serves as input to study the impact of permafrost degradation and glacier retreat on landslides (e.g. by numerical modelling).

Conclusion: Terrestrial and airborne laserscan and photogrammetry are very comprising for the reconstruction and monitoring of deep seated landslides in rough mountain environment with no direct access to infrastructure (roads and electricity). Even when remote sensing analyses delivers no subsurface information, the surface change information can be used to infer the subsurface geometry of a rock slide. The results are an essential contribution to assess the risk in the context of infrastructure, to design safety measures, and to predict the future deformation development.

INVESTIGATION OF MASS MOVEMENTS IN ALPINE ENVIRONMENTS WITH L-BAND PERSISTENT SCATTERER INTERFEROMETRY USING ALOS-2 PALSAR-2

Tazio Strozzi[1], Rafael Caduff[1], Nina Jones[1], Urs Wegmüller[1], Andrea Manconi[2]
[1]Gamma Remote Sensing, Gümligen, Switzerland, [2]Institute for Snow and Avalanche Research, Davos, Switzerland

Purpose: Ground surface deformation is an important indicator of spatial and temporal changes in landslide phenomena. A key technique for monitoring surface motion is space-based Differential Synthetic Aperture Radar Interferometry (DInSAR). Since 2014, the availability of the Sentinel-1 mission has enhanced the ability to detect and monitor surface displacements in Alpine regions. However, the nominal performance of standard and advanced DInSAR techniques in Alpine environments is affected by some intrinsic limitations, including (i) no information in areas affected by layover/shadow, (ii) reduced or complete loss of information in vegetated areas and during snow periods, (iii) reduction or loss of displacement information for relatively large motion rates (e.g., a few cm/year) and (iv) little or no ability to detect motion occurring along the approximate north-south direction. Given these limitations, L-Band satellites have the potential to complement the higher frequency systems and, under certain conditions, provide information in vegetated areas and for comparatively large displacement rates.

Methods: Over the Alpine region, a fair number (~> 10) of ScanSAR acquisitions and a small number (~<5) of StripMap acquisitions were typically acquired since 2015 along descending tracks, while a small number of ScanSAR acquisitions and a fair number of StripMap acquisitions were acquired along ascending Tracks. ScanSAR data have a much wider swath width compared to StripMap data (i.e., 350 km vs. 70 km), but a lower nominal spatial resolution (i.e., about 40 m vs. 10 m). ScanSAR and StripMap data acquired along the same orbit can be jointly exploited on interferometric point phases in order to enhance the temporal sampling and quality of the results.

Results: A nearly complete coverage of the Swiss Alps with surface motion information could be obtained with the ScanSAR data of descending orbits. The comparison with results obtained with other SAR sensors and in-situ information indicates a high quality of these results, with many known landslides clearly identified. The ScanSAR ascending orbit results are less reliable and include some errors due to the very small data stacks. Combined StripMap and ScanSAR data at more local scale worked very well for both descending and ascending orbits, revealing widespread large-scale rock slope instabilities. There are only few gaps for too rapidly moving landslides (> 5cm/year) and in particular for landslides characterized by strong acceleration or deceleration in recent years, such as the well-known Brienz and Moosfluh landslides, respectively. Overall, the achieved spatial coverage is excellent and many of the identified landslides are covered by both ascending and descending orbit data, increasing the confidence in the results.

Conclusions: In comparison to Sentinel-1, additional information is retrieved with L-Band particularly over some forests and for landslides moving at rates in the range of several cm/year. On the other hand, the accuracy of Sentinel-1 is higher than that of ALOS-2 PALSAR-2 for very slow-moving landslides. Overall, the interferometric processing of L-Band SAR data was found to be simpler than that of C-band data with higher coherence over vegetated areas. This raised large expectations for the upcoming ROSE-L and NISAR missions.

WIDE AREA LANDSLIDE DETECTION BY SATELLITE REMOTE SENSING TECHNIQUES

Chen Bo, Zhenhong Li
Chang'an University, Xi An Shi, China

Purpose: Landslides pose a destructive geohazard to people and infrastructure that results in hundreds of deaths and billions of dollars in damages every year. China is one of the countries worst affected by landslides in the world, and great efforts have been made to detect potential landslides over wide regions. However, a recent government work report shows that 80% of the newly formed landslides occurred outside the areas labelled as potential landslides, and 80% of them occurred in remote rural areas with limited capability of disaster prevention and mitigation. Therefore, Wide area landslide detection is a significant work in the field of geological hazards, and the integration of multi-temporal optical satellite images and spaceborne interferometric synthetic aperture radar (InSAR) appears to be an effective way to realize this.

Methods & Results: In this study, a technical framework is presented for wide area landslide detection: (i) multi-temporal satellite optical images are used to detect landslides with distinguishable geomorphological features; (ii) Generic Atmospheric Correction Online Service (GACOS) assisted InSAR stacking is employed to generate annual surface displacement rate maps in radar line of sight using satellite SAR images from both ascending and descending tracks, which are in turn utilized to automatically detect active landslides from ground motion using hotspot analysis; and (iii) the distribution characteristics of the detected landslides are investigated by examining their relationships with topographic and hydrological factors. Three expressways in Sichuan Province, China – namely the Yakang (Ya'an-Kangding), Yaxi (Ya'an-Xichang) and Lushi (Luding-Shimian) expressways – and their surrounding regions (a total area of approximately 20,000 square kilometers) were chosen as the study area. A total of 413 landslides were detected, among which 320 were detected using multi-temporal satellite optical images and 109 were detected using GACOS assisted InSAR stacking. It should be noted that only 16 landslides were detected by both approaches; these landslides all exhibited not only obvious geomorphological features but also ground motion. A statistical analysis of the topographic and hydrological factors shows that, of the detected landslides: 81% are distributed at elevations of 1,000-2,500 m, over 60% lie within the elevation range of 100~400 m, 90% present with medium and steep slopes (20°~45°), and 80% are located within areas seeing an annual rainfall of 950~1,050 mm. Nine landslides were found to pose potential safety hazards to the expressways.

Conclusions: The technical framework proposed in this study can significantly reduce the rate of missed landslides. The research findings have directly benefitted the Sichuan expressways; equally important, it is believed that the technical framework will provide guidance for hazard mitigation and the prevention of transportation hazards in the future.

THE CONTRIBUTION OF GROUND MOTION IN THE DECISION MAKING PROCESSES OF THE GEOLOGICAL SURVEY OF THE AUTONOMOUS REGION FRIULI VENEZIA GULIA

Antonio Bratus, Federica Muro, Fabrizio Kranitz Gerd
Autonomous Region of Friuli Venezia Giulia - Geological Survey, Trieste, Italy

Purpose: The Geological Survey (GS) promotes studies and research in the field of applied geology aimed at knowing soil and subsoil features. The Advanced Satellite Synthetic Aperture Radar Interferometry (A-DInSAR) is an established method for mapping and monitoring landslides. Persistent Scatterers (PS) Mapping leads to the static identification of the areas with the greatest deformation. PS Monitoring provides a quantitative and continuous measurement of ground deformations with a high updating frequency.

Methods: In the context of natural disaster prevention works, the GS has decided to verify the feasibility of A-DInSAR to study landslides located in the region. The interferometric technique has intrinsic limits linked to the A-DInSAR acquisition geometries and to the physical and morphological characteristics of the slopes (land use, exposure and slope angles). The GS used A-DInSAR data acquired both from the COSMO-SkyMed satellite constellation, operating in X band, and from the Sentinel-1 constellation equipped with C-band SAR sensors.

Results: The product of a multi-temporal interferometric analysis generates displacement mean velocity maps (mm/year) and time series with a displacement value for each of the available acquisitions. The advantage of this technique is an accurate estimate of the displacements over large areas, without installing any equipment on the ground. The role of a Public Administration in a geophysical process made up of acquisition, processing and interpretation is limited to the last phase. If the acquisition of the data is due to space platforms managed by national or European structures, the processing is often committed to private entities. It is therefore considered fundamental that whoever interprets the data is aware of the process and is able to communicate with whoever processes the data, knowing above all the limits of the geophysical methodology. Control, protection and regulation are tasks for the GS. Data are available to the community and to economic operators, supported by the philosophy of knowing in order to plan and design. The Ground Motion results provided important ideas for the planning of new activities, while the combination of interferometric satellite data and digital models from LIDAR data opens up new options in detection of instability. An example is the landslides of Pegliano and Calgaretto, where unknown movements were recognized. In mapped landslides, such as Cazzaso and Cleulis, it is possible to quantify the displacement intensity along the line of sight of the satellite and to be able to link ancillary data, such as rainfall, to accelerations of the movement. In the Ligosullo and Salars landslides, the comparison of the average annual movement speeds and the time series quantified the mitigation effects of a defense work built during the measurement period. The areal and temporal diffusion of the measurement points over the built-up area are an objective tool for verifying the effectiveness of the work.

Conclusions: The comprehensive picture of the level of attention across the region provides planners and operators with vital knowledge to organize and prioritize risk mitigation measures, make better decisions and proactively avoid critical problems that arise when the phenomena in progress aren't fully understood.

ASSESSMENT OF ALPINE ROCK GLACIER ACTIVITY BY EXPLOITING SAR INTERFEROMETRIC PRODUCTS

Fabio Bovenga[1], Ilenia Argentiero[1], Antonella Belmonte[1], Alberto Refice[1], Davide Nitti[2], Raffaele Nutricato[2]
[1]National Research Council of Italy (CNR), IREA, Bari, Italy, [2]GAP S.R.L., Bari, Italy

Purpose: The Alpine setting is characterized by the presence of periglacial environments rapidly changing due to global warming. In this context, landscape evolution is affected by movements of rock glaciers. They are widespread in European Alps and significant for their content of Alpine permafrost. The external temperature is considered one of the most important factors controlling rock glacier flow variation at both inter-annual and seasonal time scales, showing mean velocities ranging from centimeters to meters per year. This study employs Multi-temporal DInSAR technique to assess the deformation evolution of the rock glaciers and to classify their activity based on DInSAR results and geomorphological features.

Methods: This work investigates the rock glacier stability in Val Senales (Italian Alps) by processing a dataset of 345 Sentinel-1 SAR images acquired between 2015 and 2022. Multi-temporal DInSAR processing has been performed by exploiting both persistent and distributed scatterers through SPINUA algorithm. Ad hoc processing strategies have been adopted in order to overcome both signal decorrelation due to changeable snow cover conditions, and aliasing due to very high displacement rates. The algorithm has been run by selecting spring-summer acquisitions and forced to search for solutions corresponding to phase changes behind the aliasing limit. The DInSAR results (both mean velocity and displacement time series) have been ingested into a GIS environment together with other informative layers such as rock glacier classes (according to [1]) optical orthoimages, multi-temporal mean SAR amplitude, DInSAR coherence maps, permafrost index map, and Difference Vegetation Index (NDVI). Then, the mean velocity has been classified by adopting the more recent classification proposed in [2]. Lastly, the rock glacier activity has been reclassified by overlapping all available informative layers.

Results: The resulting mean velocity map shows several areas affected by ground displacements. Many of these areas corresponds to areas within the border of the rock glaciers in the area of interest. A further interesting issue is related to lack of DInSAR coherent targes just within the rock glacier borders that could be related to the presence of very high displacement rates. This has been investigated by exploring changes in orthoimages from different years as well as maps of DInSAR phase and coherence. The new classification has been compared to that derived according to [1] showing several differences.

Conclusions: The Multi-temporal DInSAR technique has proved to be useful for the assessment of rock glaciers, although the interpretation of the results must be supported by other informative layers. The comparison of the two classifications shows both the usefulness of the more recent techniques and the evolution of rock glaciers in recent years due to global warming.

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EXPLORING SUBGLACIAL HYDROLOGIC CONNECTIONS FOR INTERMITTENT MOTION OF THE BARRY ARM LANDSLIDE (ALASKA, USA)

Brian Collins[1], Dennis Staley[1], Johannes Gassner[2], Charles Miles[1], Lauren Schaefer[1], Mason Einbund[1], Lorenz Meier[2], Skye Corbett[1], Gabriel Wolken[3]

[1]United States Geological Survey, Landslide Hazards Program, United States, [2]Geopraevent A.G., Switzerland, [3]Alaska Division of Geological and Geophysical Surveys, United States

Purpose: Paraglacial rockslides in coastal settings can pose risk to communities and shipping traffic due to the potential for mass-movement-induced tsunamigenesis. In southern Alaska (USA), this risk is borne out by rock slope instabilities along the flanks of recently deglaciated fjords. The Barry Arm landslide is one such instability that has been the subject of recent characterization efforts. Extending from below sea-level, where recent retreat and down wasting of the tidewater Barry Glacier has exposed a portion of the landslide toe, to approximately 1.5 km elevation, where the Cascade Glacier parallels the headscarp just 100 m away, the landslide has been intermittently active in recent decades. Here we investigate landslide movement that occurred in 2022 using ground-based interferometric synthetic aperture radar (GB-InSAR) as part of an effort to characterize potential tsunamigenic hazards.

Methods: We installed a GB-InSAR device on the slope opposite the Barry Arm landslide in July 2021. We also installed a high-resolution camera to capture images that could be used for confirming radar-detected landslide deformation and for identifying geomorphic processes occurring on the landslide surface. With an InSAR data collection interval of 10 minutes and images captured several times per day, our data provide a high temporal and spatial resolution time series of landslide motion.

Results: Our GB-InSAR monitoring captured the beginning of landslide deformation near the south lateral margin of the landslide on 21 August 2022. Initial rates of motion were on the order of 50 mm/day. One week later, on 28 August 2022, motion spread to the entire landslide and average deformation rates rose in all regions to 70 mm/day. Overall motion continued at this average speed (with some regions intermittently moving up to 210 mm/day) before a gradual slowing pattern set in for the entire landslide on 13 October 2022. Cessation of all landslide movement occurred on 8 November 2022. Cumulative downslope motion totaled from 1 and 3 m within various regions of the landslide. We identified a potential triggering connection with subsurface seepage revealed by springs on the landslide surface and that likely emanates from the Cascade Glacier. Models of glacier depth behind the headscarp (Farinotti et al. 2019) indicate that the most eroded portion of the subglacial landscape aligns with the region of the landslide that first underwent motion. This suggests that the combined effects of subglacial topography and glacier melt occurring in the late summer (August) could have led to the generation of elevated pore pressures on the landslide failure plane.

Conclusions: Radar and image data from the Barry Arm landslide provide a high-resolution time series of rock slope deformation, including an entire multi-month cycle of landslide movement from initial triggering and acceleration through slowing and cessation. Observations of widespread seepage during the time of landslide deformation suggest a direct link to elevated pore pressures as a mechanism for triggering. A causal influence from subglacial hydrologic seepage is suggested from our observations, but further study is required to identify the role of other meteorological factors in modulating landslide movement.

IMPACT OF LANDSLIDES ON GLACIER DYNAMICS - PROJECT OULTINE

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Purpose: Glaciers are commonly used as indicators of climate change, with worldwide glacier retreat being one of the most iconic images of the effects of a warming climate. However, glaciers respond not only to changes in climate but also to other (e.g., tectonic activity, landslides) changes in local environment. For example, large landslides can affect the dynamics of glaciers by several different processes, including limitation of ablation, change of driving stress, or increase in meltwater production. Our project will focus on glacier-landslide interactions and associated hazards by studying these topics on several spatial scales (global, catchment, landform).

Methods: This presentation will show the background and general ideas of the research and approaches we plan to use. An inventory of supraglacial landslides will be prepared on a global spatial scale based on the literature review and supplemented using medium resolution (10-50 m) satellite imagery (Landsat, Sentinel, Aster) combined with SAR images. General characteristics and dynamics of glaciers and landslides in the catchment scale will be mapped and quantified for several benchmark glaciers affected by large landslides. Mapping in this scale will be based on time series of high-resolution satellite imagery (0.3-1 m) and available high-resolution DEMs. Landslide characteristics will be investigated on a detailed spatial scale based on UAV data (0.05-0.10 m resolution) and field mapping.

Results: The presented workflow was tested in several glaciers located in different geographic settings where large landslides were identified in previous studies, including Svinafelljökull and Morsarjökull (Iceland); Mueller, Hooker, and Tasman glaciers in Southern Alps (New Zealand). Better availability of medium-resolution satellite data after 2015 enabled us to identify hotspots (e.g., Hooker and Tasman glaciers) where supraglacial landslides occur regularly (3-5 events after 2015) but delivered a relatively small amount of debris (area covered by debris from 0.1 to 0.5 km2). In contrast, Svinafelljökull and Morsarjökull experienced single but much larger events (supraglacial area covered by debris up to 7.7 km2).

Conclusions: We were able to identify new deposits delivered by mass movements onto the glacier surface and roughly estimate their displacements and sequestration time. This research was funded by National Science Centre, Poland, project number 2021/42/E/ST10/00186

CHARACTERIZATION OF LANDSLIDE MOVEMENT BEFORE AND AFTER IMPOUNDMENTS AT THE MAOERGAI RESERVOIR (CHINA) USING MULTI-TEMPORAL INSAR

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Purpose: Hydroelectric power is the most widely utilized form of renewable energy, accounting for more than 18 percent of the world's total power generation capacity. China is the leading country in terms of hydroelectricity generation worldwide, with approximately 46,700 hydroelectric power plants and 1,300 terawatt hours generated from hydro sources. The construction of the dam also brought about many engineering geology problems, such as the formation of new landslides and the reactivation of ancient landslides followed the impoundments. For example, more than 670 landslides have been reactivated and eight landslides have failed since the impoundment of the Three Gorges Reservoir in June 2003, which seriously threatens people's safety and property. Therefore, the deformation and failure mechanism of the reservoir landslides has always been a topic of special interest in the fields of engineering geology. However, reservoir landslides are often difficult to conduct conventional deformation monitoring due to steep slopes and remote sites. In the past decades, the development of spaceborne Interferometric Synthetic Aperture Radar (InSAR) technology and the free policy of European Space Agency (ESA) Sentinel data have made the wide-area detection and real-time monitoring of landslides routine tasks.

Methods & Results: In this study, we used the ALOS-1/2 and Sentinel-1 datasets to explore the spatial patterns and temporal evolution characteristics of landslides before and after the impoundment at the Maoergai (MEG) reservoir, China. First, the deformation rates and time series of multi-platform data sources were obtained using the StaMPS/SBAS package. Note that the ALOS-1 data acquisition time is prior to impoundment. Second, the Xierguazi-Mawo landslide complex (XMLC), located 3 km west of the MEG dam, was selected for further analysis of landslide kinematic behavior after impoundment. Finally, we used wavelet tool to reveal the time lag between slope motion and reservoir water fluctuations. The observation results show that there are seven active slopes in the reservoir area before impoundment, while the number increased to 47 after impoundment, including 34 wading landslides. The feature points located in different parts of the XMLC show an increase in deformation rate compared to that before the impoundment. Moreover, the short periods of acceleration displacement signal of the Mawo sliding block may be caused by heavy rainfall, while the seasonal periodic deformation of the Xierguazi sliding block may be related to the reservoir storage-release cycle. Wavelet analysis shows that the accelerated movement of Xierguazi sliding block occurs about 120 days after the rapid decline of reservoir water level.

Conclusions: Our research reveals that impoundment changes the spatial pattern and temporal evolution characteristics of active landslides in Maoergai Reservoir area, which is proved by InSAR measurement from multi-orbit SAR datasets. The study provides an important reference for the management and risk assessment of reservoir landslides.

ROCK FAILURE ANALYSIS OF AN UNSTABLE ALPINE SLOPE USING REMOTE SENSING AND VOLUME FREQUENCY RELATIONSHIP: THE BRENVA INSTABILITY CASE STUDY (AOSTA VALLEY, ITALY)

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Purpose: The occurrence of rockfalls, rockslides, and rock avalanches in the Alps significantly alter the mountain topography and pose high risks to residents and infrastructure below the failure source area or along the propagation path. The Brenva rockslide scar, located in Aosta Valley, Italy, was formed by a large rock avalanche in 1997 and reactivated in 2016 with a volume of 3.5 × 104 m3, likely indicating a new instability cycle of this rock slope, particularly under the accelerating global warming around the Mont Blanc massif. Therefore, analyzing rock failure activity and defining potential failure scenarios for this scar are crucial for both mitigation and risk management purposes.

Methods: Structure-from-Motion (SfM) photogrammetry surveys were conducted once a year from 2017 to 2021, to track the rock failure evolution and document the inventory of the fallen blocks on this rock slope instability. The rock failure frequency-volume relationship was fitted by a power law, which was utilized to estimate the return period. Potential failure scenarios were defined using structural analysis and the slope local base level (SLBL) method.

Results: As of September 2021, 39 rockfall sources were detected with a total volume of 2.2 × 104 m3. The preliminary results suggest that rock failure activity seems to have decreased in recent years since 2017, but this does not imply that the instability will be stable from a long-term perspective. The frequent rock collapses reported during the hot summer of 2022 in the Mont Blanc massif once again demonstrated the influence of climate change on increasing rock failure activity. A new rockfall inventory from 2021 to 2023 will be established through continued remote surveys this summer, providing valuable data to update the power law and improve the return period estimation for the seven defined failure scenarios (S1 to S7) range from 3.1 × 104 m3 to 4.8 × 106 m3. Based on the extrapolated return periods derived by the power-law fit, larger failure scenarios have longer return periods. S1 (3.1 × 104 m3) has a 50% chance of occurring every 4 years, while S7 (4.8 × 106 m3) may occur once every 35 years. Although the median return period of S7 is 35 years, the 95% and 68.2% confidence intervals range from 9 to 448 years and 16 to 108 years, respectively. These ranges reflect a high level of uncertainty, but they are realistic considering the impact of global warming and progressive instability.

Conclusions: Continuous remote sensing survey is essential for monitoring rockfall activity in the Alps, especially under climate change. In addition to characterizing recent rock failure activities in high mountains, this study provides a preliminary examination of the return periods of extreme scenarios and offers essential data for risk management in mountainous areas that are highly sensitive to global warming.

DEFORMATION ANALYSIS AND GEOLOGICAL CHARACTERISATION OF AN ACTIVE DEEP-SEATED ROCKSLIDE NEAR LAATSCH (SOUTH TYROL, ITALY)

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Purpose: This article presents the case study of an alpine, deep-seated rockslide in the Val Müstair near Laatsch (South Tyrol) with focus on interpreting its deformation processes and failure mechanisms. The rockslide is situated in metamorphic rock units of the Central Austroalpine basement in a tectonically highly stressed area with numerous fault zones. The present rocks belong to the unit of the Sesvenna Crystalline, which is mainly formed by poly-metamorphic orthogneisses with intercalations of amphibolites, phyllites, paragneisses and marbles. Next to tectonic imprint, additional landscape overprint by glaciers took place forming an U-shaped valley. Melting of the ice masses were leaving oversteepened slopes and altered groundwater flow behind, which already in the past led to the destabilization of the valley flanks and consequently to the formation of ancient mass movements.

Methods: Via geomorphological and structural geological analysis and multi-temporal TLS, a failure scenario was developed leading into the interpretation of a fully persistent, slightly curvilinear basal shear zone approx. 30 to 50 Meters in depth.

Results: Along this sliding surface, rock material is transported as individual slabs recognizable on surface as main and minor scarps. The upper part of the slope shows mainly a translational movement behavior with minor internal deformation turning into rockfall at the foot of the slope. The Müstair rockslide shows an extension of approx. 400 m in NE-SW-direction and ranges 650 m from 1450 m a.s.l. to the main scarp at 2015 m a.s.l. The SE-facing slope shows a main slope inclination of approx. 35° (min. 20°, max. 80°). A total rockslide volume could be estimated at approx. 3 to 4 Mm^3. First signs of a destabilization were identified in 2011 by rock fall and block fall to the road underneath. Between the year 2011 and 2014 orthoimage analyses shows an accumulated offset of approx. 40 m with max. deformation rates of at least 9 m per month during the main formation phase in 2014 documented via multi-temporal deformation analysis based on orthoimages, airborne and terrestrial laser scanning (ALS, TLS). Continuous TLS-monitoring between 2017 and 2022 carried out 2 times a year show the deceleration of the rock slide to mean annual values of approx. 1 to 2.5 m per year until spring 2022. From spring to autumn 2022 the movement of the rockslide came to a standstill. This can be attributed to the low amount of precipitation in spring and summer 2022, since also previous deformation velocities showed a correlation with the respective amount of precipitation.

Conclusions: The main cause of the ongoing rockslide formation is attributed to retrogressive processes caused by long-term stress release due to topographical and hydrogeological changes of adjacent rockslide masses situated directly underneath exposing the active rockslide foot. Ongoing surveys via TLS are the basis for continuous monitoring of slope deformations. These are not only of scientific interest, but also form the basis of an early warning system to ensure the protection of infrastructure and the population.

LASERSCAN FUSION OF MULTITUDINOUS STATIONS IN A TOURISTIC GORGE REVEARLS EARLY-WARNING RELEVANT ROCKFALL DETACHMENT PATTERNS (HOELLENTALKLAMM, BAVARIAN ALPS)

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The Höllentalklamm (Höllental Gorge) in Grainau is part of the main mountaineering route to the Zugspitze and with up to 2000 daily visitors a major tourist attraction in the Bavarian Alps. Following several recent rockfall events (up to 300 m³) the TU Munich collaborates with the local Alpine Club (DAV-GAP) to detect, assess and monitor rock fall hazards in the Höllentalklamm. We combine multi-temporal terrestrial laser scanning, field mapping and the use of wireless sensor networks and evaluate the applicability of these methods for deeply incised alpine gorges.

In this study, we investigate a deeply incised and tectonically shaped alpine gorge in a well-researched mountain range (Wetterstein). For the first time, multi-temporal terrestrial laser scanning is applied in this extreme topography to (a) detect active rock fall areas, (b) identify hazardous objects pre-failure and (c) monitor potentially unstable parts of the rock face. Additionally, larger objects, such as a 600 m³ rock tower located directly above the track, are equipped with a redundant crackmeter system implemented in a wireless sensor network. After three years of biannual TLS epochs we can draw conclusions from our rockfall monitoring approach. TLS in alpine gorges is well-suited for the detection and quantification of rockfalls of several orders of magnitudes. The data also show that rockfall activity is linked stronger to structural geological features than relief only and that events above certain magnitudes have a good chance of being detected pre-failure. However, the extreme terrain and geometry of alpine gorges are a challenge for LiDAR coverage.

Here we show a benchmark rock fall hazard assessment and safety concept for Alpine gorges with high safety demands providing several years of data. This work helps to evaluate the applicability of well-established monitoring techniques in confined and inaccessible terrain (deeply incised gorges).

SESSION 5.7

TIMESCALES IN EVOLVING LANDSCAPES AFFECTING LANDSLIDE HAZARD AND RISK

LANDSCAPE EVOLUTION AS KEY TO UNDERSTANDING LANDSLIDE PATTERNS IN THE NORTHERN COLOMBIAN ANDES

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Purpose: Colombia faces great challenges given the multi-natural hazard setting near active plate boundaries and many socioeconomic conditions that seriously threaten its sustainable development. Some 85% of the Colombian population lives in areas exposed to two or more natural hazards, though mainly landslides and debris flows. Some of the most destructive landslide-related disasters in past decades have occurred in the nation, such as a catastrophic debris flow on November 13, 1985, devastating the city of Armero, and killing approximately 22,000 people. On April 1, 2017, a debris flow destroyed 17 neighborhoods of the city of Mocoa, killing over 300 people. These disasters involved entire cascades of hillslope and channel instabilities that are challenging to attribute to a single mechanism or source location.

Methods: We explore in more detail this interaction between channel and hillslope processes in the tectonically and volcanically active Andes of northern Colombia. We used techniques of quantitative geomorphology drawing on digital elevation models, geology, environmental conditions and landslide inventories to study the intensity, spatial, and temporal patterns of landslides in relation to metrics of landscape evolution.

Results: We find that the distribution of these landslides is explained to large parts by tectonic perturbations that we infer from various metrics for the drainage networks. Historic landslides cluster especially along transient and actively shifting divides, where geomorphic process rates are high and landslides abound, whereas older landslide deposits occur farther away from these transient belts.

Conclusions: Our results indicate that integrating aspects of landscape evolution may aid the understanding and prediction of recent landslide clusters in the Colombian Andes.

SIMULATION AND RISK ASSESSMENT OF LANDSLIDE -- DEBRIS HAZARD CHAIN IN TYPICAL DEBRIS FLOW GULLY

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Purpose: In the surrounding areas of the Qinghai-Tibet Plateau, with the climate change and the intensification of human activities, the activity of the treated debris flow gully is significantly increasing. In the past, the prevention and control of debris flow gullies mainly focused on the construction of retaining dams, while ignoring the treatment of unstable sediments in slopes and gullies, especially the treatment of potential landslides. With the passage of time, the potential landslide mass continues to transport materials for the ditch bed and gradually accumulates in the reservoir area of the artificial dam. These substances will not only inhibit the rapid flow of water in the ditch bed, but also affect the stress state of the dam body, making the dam more vulnerable to damage. When extreme rainfall occurs in the basin, the stability of the deposits in the reservoir area will be reduced under the influence of water, and the risk of dam break and debris flow will increase. For example, the "8.8 Debris Flow" event in Gansu Province of China in 2010 was of this type, which caused serious human and property losses. Therefore, how to avoid the occurrence of such disasters and reduce the losses caused by disasters is an urgent problem to be solved. This paper takes the same type of debris flow gully (Ganjia gully) located in Longnan City as the research object. Through the establishment of a multi-technology comprehensive system, the potential risks of the debris flow gully after the project treatment are studied, analyzed and evaluated, and the corresponding prevention measures are proposed. The research results will provide scientific basis and data support for the emergency response and disaster prevention and mitigation of debris flow disasters in the region.

Methods: Field surveys, including geological and geomorphological investigations, time-series InSAR technology, laboratory test and snumerical simulation were involved in this study.

Results: The study shows that the landslide in Ganjiagou basin provides the main material basis for the development of debris flow, and the material in the gully bed is the main material source when the debris flow starts. The capacity of the existing retaining works in the basin is full, and the artificial dam presents different degrees of damage. When encountering extreme rainfall conditions, it is very likely to induce catastrophic debris flow events. Based on the above research, we have evaluated the risk of potential debris flow disasters, defined the threat levels of different regions, and put forward corresponding risk avoidance and prevention measures.

Conclusions: With the passage of time and the change of climate, the mud-rock flow gully that has been treated is not absolutely safe, and negligence in prevention often leads to disastrous consequences. Systematic investigation and evaluation of the debris flow gully after early treatment, comprehensive analysis of the potential risks and threats it may cause, and scientific and reasonable prevention measures will effectively reduce the losses caused by the debris flow geological disasters.

NOVEL EVIDENCE OF A MASS ROCK CREEP DEFORMING SLOPE IN THE MOUNTAIN FRONT FAULT OF THE LORESTAN REGION OF THE ZAGROS BELT (IRAN)

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Purpose: A Deep-seated Gravitational Slope Deformation (DGSD) affects the SE slope of the Siah Kuh anticline in the Lorestan arc (Zagros Mts., Iran), upstream to the intersection between the Mountain Front Fault (MFF) and the Balarud fault zone. The DGSD is driven by a Mass Rock Creep (MRC) process and involves an area of about 8 km2. The DSGD is strictly related to the evolution of the Dowairij River drainage system as well as to the tectonic and structural setting of the MFF. Nevertheless, this instability has not been yet documented in previous studies, and the magnitude of the coupled effect related to time-dependent rock mass deformations, tectonics and landscape evolution rates remain unresolved.

Methods: In this regard, we present an integrated study, based on quantitative geomorphic analysis, optically stimulated luminescence (OSL) dating, and InSAR techniques to assess the long-term to present-day landscaping processes. In detail, we semi-automatically extracted the fluvial treads to which we associated an elevation above the thalweg based on the Relative Elevation Model (REM) allowing the order definition.

Results: Then, OSL technique was used to date two strath terraces located across the MFF, whose plano-altimetric distribution has been correlated along the river longitudinal profile, allowing the estimate of an uplift rate of 2.8±0.2 mm yr-1. InSAR techniques were performed by processing 279 satellite Sentinel-1 (A and B) radar images of the ascending and descending orbit spanning from 06 October 2014 to 31 March 2019. A maximum ground displacement rate of 6 mm yr-1 associated with tension cracks and scars involving the limestone caprock in the upper slope has been observed. Consequently, the role of the inherited Jurassic extensional fault pattern in the rock damaging has been documented.

Conclusions: In a more general perspective of understanding at which creep stage the Siah-kuh deforming slope is involved, a stress-strain numerical model of the slope in back- and forward-analysis could be a reliable tool to assess risk scenarios, after calibrating it on presently collected evidence.

PALEOLANDSLIDES ON THE SOUTHERN EDGE OF THE LARZAC PLATEAU

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Purpose: The Larzac carbonate plateau (France), is subject to numerous slope instabilities on its edges, ranging from toppling to landslides. Due to their extremely slow slip rates (3mm/year), these last large rotational instabilities of the Larzac plateau remain poorly understood, particularly in terms of characterisation and dynamics. Our study focuses on several deep paleolandslides of this type, located in two valleys: the Lergue and the Laurounet. These rotational landslides evolve in sedimentary rocks ranging from the highly fractured Jurassic (Hettangian) carbonate plateau to the Triassic (Ladinian) median sandstone via Triassic (Norian) evaporite clays. This work aims to study the initial phase's triggering mechanisms.

Methods: Photogrammetric and lasergrammetric surveys were used to map the palaeolandslides to determine the main geomorphological features. These surveys were completed by measurements of the layering planes. Also, the fracturing of the rock mass in which landslides are located was characterised by measurements of their strikes and dips. Mechanical characterisation was also carried out using the Rock Mass Rating (RMR)/ Geological Strength Index (GSI). To integrate the instabilities studied in time, the exposure age of several landslide scarps was determined with terrestrial cosmogenic nuclides using 36Cl for carbonate surfaces.

Results: Field surveys and remote sensing techniques have enabled precise mapping of the landslides and have constrained the geological model. Surveys of the orientation of joints showed that the upper unit is cut by a dense network of discontinuities. Three families are present: layering planes, and subvertical joints with NNW-SSE and WSW-ENE strikes. On these joints, the RMR and GSI classification was applied and were found to be lower at the slide units than at the in-place units. Mapping of the landslide scarps and characterisation of the joints revealed a directional correlation between the NNW-SSE family and an N-S fault network with the landslide scarps. The dating carried out on 4 scarps of two different paleolandslides showed a period of between 8 and 30 kyr depending on the denudation rate of these surfaces.

Conclusions: The recognition of landslides was made possible thanks to multi-method approaches combining remote sensing approaches and verification of field surveys despite abraded landscapes. The behaviour due to the lithologies difference between carbonates and clays of those landslides is then rotational-translational. However, the rotation of the blocks seems to be linked to the dense fracturing present on the carbonate plateau. The faults near these instabilities clearly constituted a large zone of weakness serving for initiation with the fractures or as lateral ramps. Preliminary dating determined a period when these landslides occurred towards the late Pleistocene either the end of the last glacial maximum. During this period, increasing precipitation and the incision of the rivers could have led to a rupture of the slopes in the valleys of the Lergue and Laurounet, about the dense joint networks.

MULTISTAGE EVOLUTION OF COASTAL SLOPES AS A PROXY FOR THE CLIMATIC INFLUENCE ON LANDSLIDES

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Purpose: Landslide processes are strongly influenced by climatic factors at different temporal and spatial scales. Although climatic and associated hydrogeological factors are unequivocally some of the most important drivers of mass movements, mechanisms by which climate changes affect landslides are far from being well-framed. This study focuses on landslides affecting coastal areas, since they are expected to record the most effective influence of sea-level oscillations due to climatic changes. Starting from the literature case-study of the Vasto landslide (Central Italy), on which sea-level rise effects were outlined, this research focuses on the similar case-study of Petacciato landslide, a huge roto-translational earth slide that involves a coastal sector over 2000 m along the coast. The landslide significantly damaged infrastructures as road, railway and buldings. To weigh the contributions of different predisposing and preparatory climate-dependent factors on the landslide evolution, a multi-modeling approach is here introduced, integrating engineering geology and morpho-evolutionary approaches.

Methods: The landslide geological and geomorphological setting was derived by the interpretation of field surveys, borehole stratigraphies and geospatial analyses carried out in GIS environment. Once the engineering-geological model was refined, a new approach based on a cascade of stress-strain and Landscape Evolution Modeling (LEM) will be implemented to better frame the landscape carving effects under a changing base level. Such a model provides the slope geometries representing the main stages of a morpho-evolutionary sequence, transferrable into stress-strain numerical models. The modeling approach is based on a sequential coupling of LEM and of Finite Element Methods (FEM) and/or Finite Difference Methods (FDM), which can differ one from each other in terms of spatial and temporal resolution.

Results: Some of the recognized landforms show spatial continuity across the area. Specifically, a detailed analysis made it possible to identify three orders of landslide terraces, progressively less preserved moving toward the shoreline. Field surveys and remote morphometric analyses have highlighted the presence of back-tilted strata, counter-slopes and pond zones able to geomorphologically constrain the terraced surfaces. In addition, a continuous scarp-shaped surface has been recognized at the base of the lowest order of terraces. The results of the multi-temporal analysis support the constraining of different kinds of landforms related to the landslide process and spatially distributed along all the slope. In particular, it has been observed that the drainage network has been entrenching as a response to the emplacement of the landslide mass. Combination of the reconstructed models, with the support of documentary sources from historical landslide reactivation, allowed to better frame the most active sector of the landslide mass, in the perspective of back-analyzing the current state of the landslide.

Conclusions: Results of the ongoing LEM analyses will be used as morphological constraints for a FEM/FDM modeling. This study aims at experiencing the analytical solutions to consider climate forcings in modeling landscape evolution of slopes, as well as their stress-strains conditions, to weight the role of preparatory climate factors on slope instabilities, discussing the possible role of landslides as “proxies” for climate changes at local and regional scales.

LANDSCAPE DYNAMICS AND RE-ACTIVATION OF LARGE-SCALE LANDSLIDES CONTROLLED BY FAULT ZONES IN THE WESTERN QINLING MOUNTAINS, CHINA

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Purpose: The Qinling Mountain range is part of an intra-continental orogenic zone lying east-west across central China. Its high elevations geographically divide China's southern subtropical zone and a warm temperate climate to the north. The western section of the mountain range is connected to the north-eastern edge of the Tibetan Plateau. It is characterized by a high relative relief and deeply incised rivers, formed because of extensive tectonic movements associated with the uplift of the Tibetan Plateau since the early Cenozoic. The Bailong River Corridor forms a significant catchment of the western Qinling mountain range with an area of 31,808 km2 and a population of some 2.8m. Neotectonic activity along NW-SE trending fault zones created a landscape characterized by high relative relief, steep slopes, and deep incised valleys. Widespread deforestation in the 1950s-90s increased landslide susceptibility. Slope instability forms a dominant hazard and more than 700 large-scale landslides have been catalogued (with some of these reaching several kilometers in length). In addition, most contributary valleys are prone to generate catastrophic debris flows. Some 22% of the population is directly impacted by these geohazards. Most slopes in this region are too steep for habitation and too difficult to cultivate; river terraces are too few to sustain population demands. Landslides often form gentle and tillable slopes for habitation and cultivation and this has resulted in these landforms gradually becoming occupied by villages and farms. Inevitably, any movement of the landslides would make great impact to the occupants. This research is aiming to make a critical analysis of landscape dynamics, mechanism of landslide re-activation and their impact on the population. The research results can be scalable to other regions in China and elsewhere.

Methods: Field surveys, including geological and geomorphological investigations, ground movement monitoring, borehole explorations and laboratory tests were involved in this study.

Results: Geological and geomorphological evidences indicate that landslides have initiated at least since the Middle Pleistocene. The tectonic originated fragmented phyllite and some significant amount of chlorite and graphite sandwiched by giant thrust faults are the main materials developing into landslidings where river or valley undercutting occurs. Majorities of the landslides appear in shallow form, not in deep-seated as being widely understood. Morphological evidence reveals that many landslides never become dormant, but remain intermittently active.

Conclusions: The intermittent re-activations of the landslides have been causing incessant hazards. For many generations, the local population has been living in this dynamic landscape and their relationship with landslides is complex and continuously evolving. Largely because of the greater risk of geohazards elsewhere in this landscape, people have tried to cope with the resultant damage and disruption from these geohazards, in ways that are similar to other communities across the intra-continental orogenic fault zones. The recent rapid increase in population has resulted in further land reclamation for habitation. Coupled with ongoing climate change, both exposure to and the magnitude-frequency of these geohazards continues to increase, posing escalating risks to lives, livelihoods and infrastructure.

SLOPE DYNAMIC PROCESSES IN A MEDIUM-LOW PERMEABILITY CATCHMENT IN CENTRAL ITALY

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Purpose: At the catchment scale, land cover changes can affect the slope dynamic, exacerbating the effects of intense rainfall. In this framework, the present study analyses rainfall-runoff transformation in a marly-calcareous-arenaceous watershed in Central Italy (La Bruna basin, 32 km2). The area is characterized by medium to low permeability soils, and the slopes are affected by different processes, such as runoff and shallow landslides. As recently reported by [1], runoff depth plays an important role when calculating the stability of shallow soil slopes. In the land-use scenario of the selected basin, we present runoff generation thresholds based on event rainfall depth and antecedent soil moisture content

Methods: The following methods and datasets are used:
- Multi-temporal land-use changes by aerial photos and Corine Land Cover datasets.
- Landslide inventories to collect information on the number, type, and distribution of slope movements.
- Rainfall depth by 3-gauge stations and satellite products (e.g., GPM IMERG). Runoff values are derived from river discharge data using the Local Minimum Method.
- Satellite soil moisture data from SSM1km Copernicus product (ESA), referring to the first 50 mm of soil (each 3-8 days since January 2015).

Results: The multitemporal aerial photo investigation shows a gradual increase in forested areas between 1954 and 2000, especially in the mountainous sector of the basin, combined with a decrease in cultivated areas. During the 1990-2018 period, the temporal analysis of the Corine Land Cover datasets shows drop-in olive cultivation, with a 10% increase in non-irrigated arable land. The land occupied by anthropic settlements remained unchanged, while a significant reduction in coniferous forests was observed in favour of mixed forests during 2006-2012. Landslides are represented mainly by rotational/translation movement in agricultural land areas, covering about 12% of the area and are triggered by short duration and intense precipitations. Moreover, intense rainfall also affects the runoff processes and slope dynamics, leading some areas to be affected by severe erosion. Exploiting a database of 64 rainfall events that occurred within the 2015-2021 period an updated runoff generation threshold for the La Bruna watershed was derived and tested on five events that occurred in 2022. The derived threshold may be used in areas with similar characteristics.

Conclusions: An integrated study about the slope dynamics in the La Bruna catchment highlighted that even more than 10 mm/5 minute rainfall deeply affected the slope dynamics. Identifying the runoff generation threshold can help understand runoff depth's role in triggering shallow landslides. The analysis allowed us to define the runoff generation threshold through event rainfall depth and the antecedent soil moisture content data at the event scale.

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RESEARCH ON FRAGMENTATION OF GLACIAL TILL UNDER FREEZE-THAW CYCLES AND IT'S EFFECT TO DEBRIS FLOW INITIATION

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Purpose: To understand the mechanism and history of debris flow activity in high mountainous area, this research focus on identify the threshold of debris flow initiation from glacial till, reveal the macro-action of debris flow initiation caused by the meso-structure change of glacial till in high mountainous, provide scientific evidence to reveal the mechanism and to mitigating the hazards of debris flow in this region.

Methods: The technical methods such as field investigation, cyclic freezing and thawing test, CT scanning, field test, physical simulation test, SEM analysis and mathematical statistics are adopted.

Results: Based on the research, the mechanism of fragmentation of glacial till under cyclic freezing and thawing are revealed, and the quantitative evaluation index of the impact of cyclic freezing and thawing on the mesostructure of glacial till is put forward. The two key critical hydraulic parameters of velocity and flow required for debris flow initiation are put forward. The change data of soil structure parameters under different cycle freezing and thawing times with the increase of cycle freezing and thawing times are obtained.

Conclusions:

1. After repeated cycles of freezing and thawing, the density of voids in cemented moraine soil increased, and the distribution increased in both directions, concentrated in the pore size of 0.05mm-0.3mm and dispersed at both ends. The density of voids in non-cemented moraine soil changed significantly after freezing and thawing, and concentrated in the pore size range of 0.01mm-0.1mm, providing a microscopic explanation for the process of moraine soil breaking into debris flow provenance.
2. During the cyclic freeze-thaw process, the water in the moraine soil mass infiltrates and migrates along the slope surface and perpendicular to the slope surface, making the water content of the slope soil mass gradually decrease from the front to the rear, and gradually increase from the surface to the bottom, which is the main internal reason for the tractive damage of the moraine slope and becoming the source of debris flow.
3. The formation of debris flow initiated by moraine soil is mainly divided into three processes: surface erosion, lateral erosion and cutting erosion. The runoff velocity is the most critical factor to control surface erosion, and its size is positively correlated with the intensity of surface erosion; Runoff flow is the most critical factor to control the lateral erosion stage of till soil, and its size is positively correlated with the lateral erosion intensity. Runoff erosion time is the most critical factor to control the erosion stage of till soil, and its size is positively correlated with the erosion intensity.
4. During the formation of debris flow from moraine soil, affected by the characteristics of large particle size grading range, the longitudinal profile shows wavy erosion characteristics, revealing the stepwise replenishment mode of coarse particles to debris flow provenance during the replenishment process of debris flow provenance in different channel sections in alpine mountains, and providing a new idea for the design of such debris flow control engineering.

RISK ASSESSMENT OF MOLI LANDSLIDE BASED ON DYNAMIC PROCESS SIMULATION IN ZHOUQU COUNTY, GANSU PROVINCE, CHINA

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Purpose: With the deepening research on geohazard risk, geohazard risk assessment and management have become important part of the international disaster prevention and mitigation strategy. Because of the intensive rainfall in rainy season, the Moli landslide, located in Guoye Town, Zhouqu County, reactivated and broke on February 26, 2021, with a volume of 2.12 × 107m3, seriously threatening 282 households and 1,119 people, and forming large landslide risk. The results can provide technical basis for the risk management of Moli landslide, and references for the quantitative risk assessment of large landslide in similar areas.

Methods: Based on the detailed investigation of landslide characteristics and displacements of reactivation, we simulated the dynamic process of landslide under extreme conditions using the continuous mechanics model, and assessed the quantitative landslide risk.

Results: The reactivation of landslide shows retrogressive process. The deformation process can be divided into two stages: local sliding stage in 0~50s and whole sliding stage after 50s. Under extreme condition, the whole landslide will run out, and block Dashuiba gully at 40s in the front edge. The maximum thickness of the dam can reach 28.3 m. The movements show interactive deformation characteristics of pushing in 0~150s and traction later after breaking. The quantitative risk assessment of Moli landslide showed that high, medium and low risk area have a percentage of 20.4%, 70.3% and 9.3% respectively.

Conclusions: The Moli landslide is in the stage of creep presently. Under extreme condition, the landslide will fail and slide as a whole block, and dam the Dashuiba gully. Due to the large magnitude and significant challenge of engineering construction for landslide risk prevention, we recommend to relocate the people threatened by the landslide. Our relocation plan based on quantitative risk assessment provides scientific foundation for emergency management and risk mitigation.

INVESTIGATION OF THE 2019 WENCHUAN COUNTY DEBRIS FLOW DISASTER SUGGESTS NONUNIFORM SPATIAL AND TEMPORAL POST-SEISMIC DEBRIS FLOW EVOLUTION PATTERNS

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Purpose: It is widely recognized that post-seismic mass movements amplify and decay. Previous studies have found that most post-seismic mass movement is concentrated in the first few years following an earthquake. A major debris flow occurred in Wenchuan County in 2019, 11 years after the 2008 Wenchuan earthquake, showing that there might be a different temporal evolution pattern. In Wenchuan Country, the area struck by the 2019 disaster was investigated to explore whether a pattern existed.

Methods: Remote sensing and field surveys investigate the initiation processes, sediment supply, and triggering rainfall.

Results: The result shows that most of the active landslides occurred in high-elevation areas where vegetation cover was lacking, and nearly half of them were reactivated landslides. The debris flows were mainly initiated by run-off erosion of debris in steep channels, and more than half of the sediment supply was from deposition along the channels in some catchments.

Conclusions:
1. The debris flows in 2019 were mainly initiated by run-off erosion of debris in steep channels.
2. Most active landslides occurred in high-elevation areas where vegetation cover was lacking, and nearly half of them were reactivated landslides. According to a quantitative sediment supply analysis, more than half of the sediment supply came from deposits in the main channel of DF9.
3. As shown by our rainfall threshold models, the catchments in the study area's northern part are more easily triggered than those in the southern part. The spatial characteristics of the regional rainfall threshold should be considered when using the rainfall threshold model to predict debris flow in the study area. Additional research should be conducted to determine the relationship between spatial variation in the debris flow rainfall threshold and catchment characteristics, debris source distribution, and evolution.
4. More debris flows occurred in the northern part of the study area, where the relative annual rainfall and coseismic landslide density are low. The average area and relief of catchments in the northern part of the study area are larger than those in the southern part. The phenomenon is presumed to be caused by the variation in sediment transportation rates and vegetation growth rates, which are affected by the climate and morphological conditions.

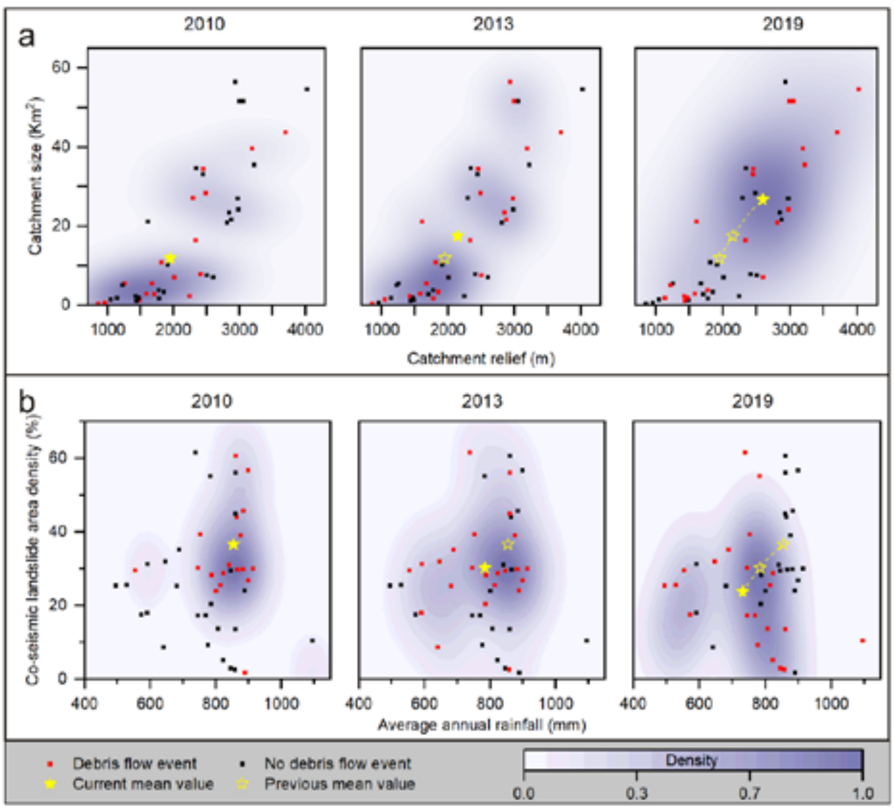

Fig. 1: Statistical results show the temporal evolution of debris-flow-active catchments. The data points include the 2019 event investigated (complete, not just the study samples) and the previous events documented by Tang and Van Westen (2016). (a) Catchment size and relief (the difference in elevation from the outlet to the top). (b) Annual rainfall and co-seismic landslide density.

ACTIVITIES AND KINEMATIC EVOLUTION OF LARGE LANDSLIDES ALONG FAULT BELT IN THE NE QINGHAI-TIBET PLATEAU

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Purpose: The Bailong River Corridor is positioned along the northeastern margin of the Tibet-Qinghai Plateau. This is a very dynamic region affected by the interplay of neotectonic deformations, variations in lithologies, changes in land use and climate. The consequence is a landscape with a high susceptibility to generate geohazards. Hundreds of large and slow-moving landslides have developed and reactivated along faults and fractured bedrock zones, posing severe threat to local lives and livelihoods. This study is aiming to present a detailed and updated landslides inventory, and to discuss their activities and kinematic evolution over the past ten years. In addition, the control and driving factors for the slow moving landslides are analyzed. This will shed some light on the mechanism of the reactivation of existing landslides and landscape evolution in the similar mountainous areas, and provide scientific basis for hazards mitigation and prevention.

Method: Interferometric Synthetic Aperture Radar, offset Tracking, landslide inventory based on optical image interpretation, multi-temporal observation using Unmanned Aerial Vehicle, high-resolution topography analysis and geomorphological survey and mapping.

Results: The results of geometric distortions indicate that most of the mapped landslides are located in areas out of distortions, providing good visibility for satellites to monitor ground deformations. Multi-source remote sensing techniques are fairly effective to detect ground deformation of large slow-moving landslides at different scale. Almost of all of the reactivated landslides have very slow movements with yearly displacements ranging between 16 mm and 1.6 m presently. Multi-temporal inventories of active landslides indicate that many large landslides have become reactivated over the past ten years. Recently, these landslides turned into more active and susceptible to intensive rainfall. The high-resolution topography analysis and geomorphological mapping revealed that majority of the large active landslides have typical morphology of elongated earthflow, parallel to fault stretches. Earthflow materials from source area are more preferential moving along the flow path under the effect of higher soil moisture content after rainfall occurrences. We found the similar clay-rich materials in all slip zones which consist of fault gauge, Quaternary deposits and fragmented metamorphic rocks. Time-series displacements exhibit a clear positive relationship between landslides movements and seasonal precipitation. The Wenchuan and Jiuzhaigou earthquake accelerated the displacement rates and promoted the evolution of landslides.

Conclusions: This research demonstrates the applicability and effectiveness of multi-source remote sensing techniques for detecting deformation of large landslides. Hundreds of active landslides show very slow speed (16 mm/yr < velocity < 1.6 m/yr) movement making a long-term contribution to the landscape evolution. Most of the landslides are developed as earthflows in early stage and predominantly congregated along fault belts. Many of landslides turn into active as a result of concentrated precipitation, earthquakes and human interactions. The weak and clay-rich materials in slip zones attribute to the weakening shear strength resulting slow mass movements even with gentle slope gradient. The reactivated landslides tend to transform into fast movement at late stage. The evolution of the mass movements reshape the regional relief towards a dynamic equilibrium of topography controlled by tectonic movements and river incisions.

SESSION 4.2

SPATIAL LANDSLIDE ASSESSMENTS AND BEYOND: NEW HALLENGES IN MAPPING, MODELLING, VALIDATION AND SCENARIO BUILDING (part I)

THE APPLICATION OF GIS-BASED LOGISTIC REGRESSION ANALYSIS FOR LANDSLIDE SUSCEPTIBILITY MAPPING: A CASE STUDY IN WESTERN ALBANIA

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This paper presents the landslide susceptibility map for the hilly area of the Adriatic plain in western Albania. The study area consists of a hilly relief with relatively steep slopes composed of terrigenous Pliocene deposits overlaid by weathering products (soils) at the top. The study zone has an area of about 97 square kilometers, of which about 4 square kilometers are affected by landslides. The landslide susceptibility map for the study area was produced using Logistic Regression Analysis, which represents one of the most used methods to predict the occurrence of landslides by fitting the data to a logistic regression function. The dataset preparation and the analysis was performed in GIS using a grid of 25 x 25 m2 pixels. The Logistic Regression Analysis was trained using 265 landslides from 379 landslides, mapped using different techniques such as field mapping and remote sensing data (Lidar, Sentinel 2 images, Google Earth, etc.). A set of 14 causative factors maps were prepared and analyzed to check the conditional independence by the use of chi-squared statistical test. After the analysis nine factors resulted to satisfy the condition of independence as follows: “Aspect”, “Distance from buildings”, “Plan Curvature”, “Profile Curvature”, “Elevation”, “Geology”, “Rainfall”, “Slope” and “Topographic Wetness Index”. The Receiver Operating Characteristic curve and Cohen’s Kappa coefficient were used to validate the susceptibility map. Six susceptibility classes were defined by the use of natural break classification method as follows: None, Very low, low, moderate, high and very high. In the moderate to very high susceptibility classes, 48 % of the study area is encountered.

Keywords: Landslide Susceptibility, logistic regression, GIS, Albania

RELATIONS BETWEEN GEOTECHNICAL AND MINERALOGICAL PROPERTIES OF MATERIALS AND MID TERM EVOLUTION OF EARTHFLOWS

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Purpose: Earthflows are characterized by a gradual movement of soil down a slope, often due to gravity and water saturation. Earthflows are commonly found in regions with uneven terrain and moderate to high elevations, where a combination of weak rocks and clay do exist on moderately sloping surfaces with sufficient moisture. Unlike a typical landslide, which can occur suddenly and rapidly, an earthflow is a slower, more gradual movement that can persist for months, years or tens of years. Extraordinary records of earthflow movements account for two to four centuries-long persistent movement. While earthflow evolution is typically characterized by periods of slow movements alternated with dormancy, under certain conditions, some earthflows may experience unexpected surges in movement. Surge development can be associated with a shift in the earthflow mechanism from sliding-dominated to flow-dominated, resulting from material fluidization. Surges can cause significant damage to infrastructure and settlements and are difficult to be predicted due to their unpredictable nature and poor constraint of controlling factors. To contribute to a better understanding of the process of surge development and the susceptibility to solid-to-fluid behavioral transition of earthflow materials, this study presents the results of geotechnical and mineralogical characterization and mid-term temporal evolutionary reconstruction of fourteen earthflows in the southern Apennines range of Italy.

Methods: The selection of earthflows is based on their ability to represent different geomorphological conditions and materials (i.e. source geological formation) that could have undergone a transition from a solid state to a fluid state, leading to surges in movement. For each site, remolded soil samples were gathered and used for mineralogical and geotechnical laboratory analyses, including quantitative X-ray powder diffraction analyses performed on clay fractions (d <75 µm) separated from the bulk samples, mixed to corundum (20 wt.%) and then micronized (grain size <10 µm), grain-size analysis, specific gravity measurement, Atterberg limits and oedometer tests.

Results: The mineralogical analyses highlighted ubiquitous quartz and phyllosilicates such as chlorite and/or kaolinite along with variable amount of low-ordered structures/amorphous phases, feldspars (mainly plagioclase), carbonates (calcite and subordinately dolomite), and traces of oxides. Geotechincal analyses allowed us to observe that the samples of the fourteen landslides analyzed are mostly characterized by a minimum of 60% clay and silt from a granulometric point of view, a medium to high plasticity index, an oedometer modulus from 33,5 MPa to 48,0 MPa and a compressibility coefficient ranging from 0,192 to 0,325.

Conclusions: The data were interpreted in the context of potential solid-to-fluid transition susceptibility, considering the mid-term evolution of the earthflows reconstructed through visual interpretation of multi-temporal satellite images. This evolutionary reconstruction allowed to understand if considered earthflows have evolved through surging episodes. On the basis of these data, a PCA analysis has been completed to identify potential behavioral groups. Results from the PCA analysis will form a basis for further analysis aimed at understanding the process behind solid-to-fluid transition.

DEVELOPMENT OF LANDSLIDE DOMAIN MAPS AT REGIONAL SCALE IN DATA POOR AREAS UNDERLAIN BY TROPICAL RESIDUAL SOILS

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Purpose: Effective landslide forecasting systems draw from an understanding of the spatial distribution of areas that are likely to be prone to landsliding together with knowledge of the magnitude of the triggering input required to drive the landsliding. With the right data, landslide forecasting systems can be refined by landslide type (hazard characterisation) and the antecedent conditions. The scale of application informs the scale and type of the modelling data requirement. For example, the contributory data informing the conditioning factors available for susceptibility mapping at the national scale with variable densities of data utilises datasets that are increasingly satellite derived. However, as we move to the regional scale of landslide characterisation in data poor areas (e.g., landslide inventory) we rely increasingly on ground-based process understanding, thereby moving closer to deterministic modelling to achieve the required resolution of modelling for developing rainfall trigger threshold values. This demands an increase in the number and spatial resolution of the contributory factors; a particular challenge in data poor area. Two of the key components requiring greater resolution in this context are geotechnical (grain-size, shear strength, anisotropy, density) and hydrogeological (aquifer, aquitard, flow characteristics and head) parameters.

Methods: To enable this in the region of Idukki in the Western Ghats area of India we have taken a nested domains approach, in which different conditioning and process-relevant factors influencing landsliding are stacked above each other in a systematic and logical sequence. Specifically, we overlap tectonic terrain units, bedrock geology and structure, superficial geology, soils mapping and vegetation to characterise land units with similar characteristics at the regional scale.

Results: The use of domains facilitates the derivation of material property attributions (input parameters) for incorporation in the regional scale modelling using Open Source code, such as TRIGRS, Scoops3D, or Flow-R. Literature- and stakeholder-informed derived data are presented as characteristic weathering profiles, geotechnical and hydrological domain attributes for integration with the primary domains to inform the landslide modelling. Limited, locally sourced field data provides a means of validating the derived data, which relies on a component of expert judgement and elicitation. Satellite-derived landslide data facilitates localised validation of the modelling. A collaborative, stakeholder, local knowledge-based approach is fundamental to the success of this domains approach, as a precursor to trigger threshold modelling.

Conclusions: For the landslide work in Idukki and the development of rainfall trigger threshold values, domains represent one fundamental part and it is planned to analyze in the course of the ongoing project how this can be transferred to other areas.

DEVELOPMENT OF A PROTOTYPE DATA-DRIVEN MODEL TO DEFINE THE TRANSIENT SUSCEPTIBILITY TO SHALLOW LANDSLIDES FOR OPERATIONAL PURPOES IN AOSTA VALLEY (ITALY)

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Purpose: This study aimed to develop a prototype data-driven model for the prediction of shallow landslides occurrence for operational purposes. Specific objectives included: i) testing different dynamic hydrometeorological predictors; ii) defining a strategy to sample non-landslide events for an effective model construction; iii) deriving a parsimonious and reliable model in terms of number of predictors and their geomorphological plausibility; iv) validating of the model against occurred scenarios.

Methods: The data-driven model was developed based on slope units (SUs) and using Generalized Additive Models (GAMs). The model was developed on a daily timestep for the period 2009-2020, being the temporal information included in the available landslide inventory limited to the day of the events (n. 148). Both static (morphometric, geological, geometrical) and transient (rainfall and soil moisture) predictors were considered. The tested precipitation variables were derived based on cumulative values, statistical distributions and operational thresholds. Soil moisture variables were derived based on antecedent conditions (actual values at 00.00 hours of the modelled day), variations in comparison to previous days and their statistical distributions. To select subsets of non-landslide conditions, four strategies were tested: i) 1:1 ratio between landslide and non-landslide conditions with non-landslide conditions selected within the SUs with recorded landslides on days with no events; ii) 1:1 ratio with non-landslide conditions selected among SUs with no landslides on days with recorded events; iii) 1:1 ratio with non-landslide conditions randomly selected both spatially and temporally; iv) the combination of the three previous options resulting in a 1:3 ratio. For model optimization, predictors were checked for geomorphological plausibility through Component Smoothing Functions. Statistical significance was considered activating the shrinkage option of the used gam function (mgcv library, R environment). The quantitative model performance was evaluated through AUROC. The relative importance of the predictors was checked calculating the mean decrease of deviance explained (mDD%). All these aspects were also checked in the framework of a k-fold random cross-validation. For predictive capacity testing, six days (scenarios) were selected in the 2009-2020 period in which at least three events occurred. Model performances were evaluated through AUROC and confusion matrices.

Results: The non-landslide sampling strategies yielding the best model performances are the third - Model-3 - and the fourth - Model-4 - (AUROC of 0.89 and 0.80, respectively). Model-3 included 11 predictors, while Model-4 just six. In both optimized models, two rainfall predictors and a soil moisture predictor are included, explaining in total about 22% and 32% of the model deviance, respectively. The evaluation for scenarios showed a better performance of the third sampling strategy in comparison to the fourth for False Negatives, but a worse one regarding False alarms (Figure 1).

Scenario	*Scenario 1 26-04-2009*					*Scenario 2 19-05-2013*				
#n landslides	3					5				
Sampling strategy	AUROC	FP False alarms	FN Miss	TP	TN	AUROC	FP False alarms	FN Miss	TP	TN
Model-1	0.82	110	2	1	786	0.69	894	0	5	0
Model-2	0.74	276	1	2	620	0.86	425	0	5	469
Model-3	0.84	322	0	3	574	0.69	714	0	5	180
Model-4	0.85	3	3	0	893	0.93	403	0	5	491
Scenario	*Scenario 3 08-01-2018*					*Scenario 4 27-10-2018*				
#n landslides	10					4				
Sampling strategy	AUROC	FP False alarms	FN Miss	TP	TN	AUROC	FP False alarms	FN Miss	TP	TN
Model-1	0.73	889	10	0	0	0.35	413	3	1	482
Model-2	0.90	398	0	10	491	0.68	281	2	2	614
Model-3	0.79	743	0	10	146	0.65	457	0	4	438
Model-4	0.87	334	1	9	555	0.67	14	4	0	881
Scenario	*Scenario 5 24-11-2019*					*Scenario 6 03-10-2020*				
#n landslides	7					12				
Sampling strategy	AUROC	FP False alarms	FN Miss	TP	TN	AUROC	FP False alarms	FN Miss	TP	TN
Model-1	0.80	814	0	7	78	0.53	887	0	12	0
Model-2	0.88	396	0	7	496	0.75	475	1	11	412
Model-3	0.90	671	0	7	221	0.71	799	0	12	88
Model-4	0.89	389	0	7	503	0.77	604	0	12	283

AUROC: Area Under the Receiver Operating Characteristic curve
TP: True Positive TN: True negative FP: False Positive FN: False Negative

Fig. 1: Results for sampling strategies and scenarios.

Conclusions: Despite the best quantitative performance, Model-3 is considered not robust because results are expected to be highly dependent on the random selection of non-landslide conditions (5 million available options and just 148 selected). Results obtained with Model-4 are promising. Further tests are needed possibly incorporating soil moisture data with hourly time resolution.

LiDAR-BASED IDENTIFICATION, MAPPING AND INVENTORY OF SLOPE DEFORMATIONS IN BIELE KARPATY MTS

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Purpose: Atlas of Slope Stability Maps of the Slovak Republic in the scale 1:50,000 was compiled between 1999 and 2006. It processed with a uniform methodology all slope deformations mapped and registered on the territory of Slovakia until then. However, with the onset of new remote sensing technologies enabling discrimination of geological objects in larger scales, the State Geological Institute of Dionýz Štúr has adopted them, particularly in solving the emergency landslides. The pilot study was carried out in Vrátna catastrophic debris flows mapping in 2014.

Methods: Improving the landslide risks prevention by defining the risk of slope deformation in geological environment prone to landslides within the Slovak Republic, is the primary objective of the geological task Identification, Inventory and Engineering Geological Mapping of Slope Deformations planned for 2018-2023 under the umbrella of the Operational Programme Quality of Environment. It concerns the exploration of the 5 regions across Slovakia significantly threatened by slope failures. The inventory itself is preceded by the creation of a detailed digital terrain model DTM 5.0, provided by Geodesy, Cartography and Cadastre Authority of the Slovak Republic, generated from airborne LiDAR data with a detailed capture of terrain elements that were caused by slope deformations and other geohazards and which are subject to mapping. It is the most widespread and very intuitive visual technique that creates a 3D representation of the terrain surface in shades of grey depending on the relative position of the Sun. It allows to identify various geomorphological forms of relief, even in hard-to-reach places and under vegetation cover. The mapping is aimed at refining the position of the covering Quaternary complexes and slope deformations and other geohazards. The mapping is followed by the updating the database and the register of slope deformations operated at SGIDS and by the preparation and creation of parametric maps necessary for the development of the landslide hazard forecast by numerical methods in the GIS environment.

Results: As a result of mapping in region of the Biele Karpaty Mts. 2,800 landslides of total area 107.30 square kilometres were registered in comparison to 850 landslides of area 92.55 square kilometres registered by Atlas of Slope Stability Maps as of 2006. A differential map of landslide near Machnáč hill was created by using interpolated LiDAR data comparison of the two differential digital terrain models (2018 vs 2021) via map algebra analysis. A colour scale was used to illustrate landform changes as the result of the mass movement.

Conclusions: We present results of slope failures mapping in the region of the Biele Karpaty Mts. by comparing with the Atlas of Slope Stability Maps of the Slovak Republic to document the significant shift forward thanks to the conveniences offered by LiDAR technology.

PRIORITIZING OF FACTOR RESPONSIBLE FOR LAND SLIDING BY ANALYTICAL HIERARCHICAL PROCESS (AHP)

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Purpose: Prioritizing of factors responsible for the landslide trigger is an essential process in landslide susceptibility analysis. This allows the researcher to recognize how important each requirement is. If time or resources are short, the least important requirements may have to be left out. An Analytic Hierarchy Process (AHP) is a quantitative technique for multiple criteria decision making (Saaty, 1994). It provides a convenient way to quantify the qualitative aspects, and eliminating subjectivity in the outcome. Factor prioritizing requirements were determined using the AHP for the Kalawana watershed in Sri Lanka.

Methods: In this method, at first, for the reason of determining different factor preferences and converting them into quantitative values, valued judgments are used. The creation of a digital terrain model was shown to be very important for a relevant landslide susceptibility analysis made in larger scale than 1: 50 000. Therefore, areas with highest landslide susceptibility were chosen to be studied in detail from the point view of slope angle or the combination of angle and slope aspect. In this study, considering all above explanations, factors contributing to destabilization of slopes are slope (S), rainfall, precipitation potential (R), hydrology, considering the number of 1 st order streams within the selected catchment (H); road buffer, considering the distance away from the edge of the road (RB); bedrock geology, due to dipping and foliation issues (BG), shear strength of the top overburdened soil (SS); and landuse (L).

Results: To obtain the relative ranks for each prediction pattern, the calculated index values of all cells in the study area were sorted in descending order. Then the ordered cell values were divided into 64 classes with accumulated reasonable interpreted intervals. The primary set of levels of the susceptibility curve creates the prediction accuracy qualitatively as shown in Figure 1.

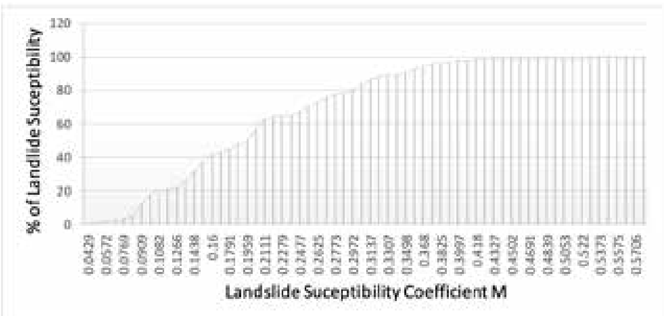

Fig. 1: Illustration of the ranking of stability class with a large database reasonably capable for evaluation of landslide susceptibility.

Conclusions: The defining of landslide susceptibility is a matter of classifying degree of instability potential using the graph of landslide susceptibility coefficient vs percentage of landslide susceptibility. This was based with the old landslide data and also considering sensitivity of occurrences. The Table 1 indicates classifying to five number of classes with the ArcGIS facility and occurrences of landslide under each category. The overall assessment is based with the 39 number of old landslides selected and verified at site. In such situation more than 84.6% of landslide are fall in the categories of moderate susceptibility to high susceptibility.

Table 1: Landslide susceptibility reclassified results - Std deviation ½ reduced to 5 classes

Class	Class Lable	Susceptibility	Count	% Area	Number of Landslides
1	0.036-0.146	No Susceptibility	1461669	38.67	4
2	0.146-0.256	Low Susceptibility	719978	18.99	2
3	0.256-0.365	Moderately Susceptibility	861153	22.8	12
4	0.365-0.475	High Susceptibility	615242	16.3	6
5	0.475-0.585 and over	Very High Susceptibility	122367	3.24	15
		total	3780409	100	39

QUANTITATIVE EARTHQUAKE-INDUCED LANDSLIDE MODEL VALIDATION OF ABRA PROVINCE, PHILIPPINES: A CASE STUDY OF THE LANDSLIDE IMPACTS OF THE 2022 JULY 27 MW 7.0 NORTHWESTERN LUZON EARTHQUAKE

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Purpose: One of the key tools to predict the hazard of landslides and to address countermeasures for areas potentially prone to future landslides is an earthquake-induced landslide (EIL) susceptibility map. Maps are highly in demand at the national and provincial levels for integration into the spatial planning strategies of the disaster risk reduction programs of the local government units. With this, the study aims to validate the methodology for the generation of an earthquake-induced landslide susceptibility map in a regional scale, under the "Deterministic Earthquake-induced Landslide Hazard Mapping in the Philippines Project in 2020" using post-earthquake landslide impact distribution. The current methodology to generate the map incorporated the use of landslide modeling techniques based on Newmark's methodology, integrated by ground shaking input with the standard landslide parameters, and validated using landslide inventories. Abra Province is presented as the case study, being the epicenter of the recent Mw 7.0 – July 27, 2022 Northwestern Luzon earthquake, and site of numerous earthquake-induced landslides.

Methods: Validation of the susceptibility map for landslide impacts was carried through landslide inventory during field investigation and interpretations of high-resolution pre- and post-earthquake remote sensing images as well as photos and videos taken by drones conducted by the Department of Science and Technology - Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS) Quick Response Team from July 28 to August 10, 2022. Terrains and mountains were evaluated based on topography, steepness and failure of geologic materials, and ground shaking acceleration to examine and quantify the causal factors for the generation of landslides.

Results: The earthquake triggered at least 681 landslides, mostly shallow (e.g rock slides, debris falls and debris slides, valley fill collapsed, and cut-and-fill failure types). Majority of the landslides were observed 10 - 20 kilometers away from the earthquake epicenter, at slopes of 30° - 40°, and with the highest susceptibility elevation ranging from 200 meters to 300 meters. Landslides occurred mostly in steep slopes, in areas that experienced strong shaking along or near ridges, and on highly-sheared and unstable geology, which indicated wave interactions in complex topography as a result of ground shaking amplifications. Using the earthquake-induced landslide inventory from the remote-sensing and field survey, we validated the predictive capability of the earthquake-induced landslide susceptibility maps.

Conclusion: Field survey and remote sensing analysis suggest that the earthquake-induced susceptibility maps generated in 2020 generally coincided with the actual landslide impact of the 2022 Mw 7.0 Northwestern Luzon earthquake in Abra. Thus, this generated map may be used for hazard assessment for various evacuation or relocation sites, land-use planning, and hazard mitigation.

REGIONAL SEISMIC LANDSLIDE HAZARDS MAPPING: A CASE STUDY USING CALIBRATED NEWMARK MODEL IN THE YINGXIU AREA, SICHUAN, CHINA

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Purpose: Although there exists controversy concerning the problem whether the earth has entered the earthquake-prone period or not, it is generally accepted that the frequency of the recent devastating earthquake is higher than that in the past. The earthquake-induced landslides are increasingly becoming the research focus of geologists. After a regional long-term earthquake prediction, it has great significance for reducing casualties and property losses if we can predict the earthquake-induced landslide prone area as well as assess the seismic landslide hazards. Therefore, it is very important to develop the conventional methods and model for spatial estimates of the likelihood of landslides due to earthquakes as well as seismic landslide hazards mapping.

Methods: In this paper, the commonly used seismic landslide hazard evaluation methods are presented. As an example, the seismic landslide hazards mapping and analysis is applied for Yingxiu area, the epicentral area of the Wenchuan Ms 8.0 earthquake on May 12, 2008, by using calibrated Newmark model. Based on the interpretation of high-resolution aerial photographs and satellite images combined with field investigation after earthquake, regionally calibrate the assessment models and procedure of the seismic landslide hazards related to Newmark model. This improvement of the Newmark method can be anticipated that the assessment models and mapping procedure will assist in emergency preparedness planning and in making rational decisions regarding development and construction in active fault zone of the southwest mountain areas susceptible to seismic slope failure.

Results: Main conclusions of the mapping and analysis are as 1) the dominated seismic geohazards within Yingxiu area are shallow, disrupted landslides and small scale rockfall and clustered in the hanging wall of the Longmenshan Central fault; 2) several deep-seated landslides or rock avalanches with long run-out located near or at the Longmenshan Central fault ruptures; 3) the seismic geohazards evolution in Yingxiu area are probably controlled by the earthquake magnitude, the rugged topography and fragile lithology; 4) the man-made steep slopes, such as slope-cut in order to build road or house, can be severely damaged during this Wenchuan earthquake and formed rockfall or landslide; 5)the Wenchuan earthquake disturbs the slope bedrock and creates an amount of loose material on the slopes. It affects the stability of these slopes for a long period of time and needs pay more attention to prevent the secondary hazards such as debris flow after the earthquake.

Conclusions: The calibrated Newmark Model is a feasible and efficient method which can show the landslides failure probability for specific ground-shaking conditions and depict a possible scenario of hazards due to earthquake-induced landslides in southwest mountainous areas, China. It must be regionally calibrated when this method is applied to other areas.

Keywords: Earthquake-induced landslides; Hazard assessment; Hazard Mapping; Wenchuan earthquake

RESIDUAL LANDSLIDE HAZARD ON SLOPES COVERED BY PYROCLASTIC DEPOSITS: LESSON LEARNED FROM THE PALMA CAMPANIA EVENTS IN SOUTHERN ITALY

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Purpose: Flow-like landslides triggered by rainfall are a major concern in the peri-Vesuvian region of southern Italy. On December 19th, 2019, a landslide occurred along the Crocelle slope (Sarno Mountains) as a consequence of an intense rainfall event (~100 mm of rainfall in 20 hours), which had previously experienced a similar event in February 1986. This landslide was characterized by a limited magnitude if compared to the event that occurred in February 1986 along a different gully of the same slope, and resulted in no victims and no damage to human settlements due to the presence of mitigation measures at the slope foot, unlike the 1986 Palma Campania landslide that caused eight casualties and settlements destruction. This study was conducted to assess the characteristics of this event in terms of triggering and propagation conditions and, with reference to the 1986 landslide, to evaluate the evolution of landslide hazards at recurring landslide sites.

Methods: In this framework, we conducted a comprehensive analysis focused on understanding the main characteristics of the 2019 Palma Campania landslide in terms of triggering and propagation conditions, also to compare them with those related to the 1986 landslide. To this aim, some analyses were carried out based on: i) field survey, ii) geotechnical laboratory testing on soil samples collected in the source area, iii) statistical analysis of triggering rainfall, iv) hydrological modeling and slope stability analysis and v) propagation modeling.

Results: Landslide-source area characters were reconstructed from a UAV-based photogrammetric survey estimating the initial landslide volume in ~450 m3. In-situ observations, completed at the edge of the source zone, allowed the identification of involved material, which appears to consist in a reworked pyroclastic deposits. The return period of the triggering rainstorm for specific durations was estimated by rainfall analysis in approximately 4 years, whereas hydrologic modeling and slope instability analyses have allowed identifying critical triggering conditions in terms of rainfall intensity and duration that took place after 13 h from the beginning of the rainfall event. Finally, propagation modeling was conducted to reconstruct landslide mechanism, total thickness of the deposit and flow velocity. Results show that the landslide mass moved from the detachment to the deposit area with an estimated maximum velocity of ~10 m/s, obtaining a good correlation between the estimated and measured thickness of landslide deposits.

Conclusion: Comparison of the 2019 event with the 1986 event revealed a significant difference in terms of landslide magnitude (i.e., volume), potentially due to the occurrence of multiple events, which may have led to the temporal depletion of available materials along a slope repeatedly affected by landslides, and possibly to the different behavior of primary layered deposits (involved in the 1986 event) compared to reworked deposits (involved in the 2019 event). This suggests a reduction in the residual landslide hazard associated with a decrease in the expected magnitude and frequency of prospective events. Implication of this finding is that hazard evaluation at recurrent landslide sites require post-event hazard re-estimation that con not be based on a magnitude equivalent scenario.

AN INTEGRATED PROBABILISTIC MECHANISM-DRIVEN AND DATA-DRIVEN APPROACH TO LOESS LANDSLIDE RISK ASSESSMENT AT REGIONAL SCALE: AN EXAMPLE FROM CHENGGUAN DISTRICT OF LANZHOU CITY, CHINA

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Purpose: Landslide risk is an intersection of several components, including hazard, vulnerability, and elements at risk as well as their amounts, or hazard and potential worth of loss. However, the quantification of these components with consideration of their nature is complex and challenging. In landslide hazard assessment, the determination of magnitude is the most critical stage in addition to spatial location and time recurrence, which is driven by failure mechanism of different types of slopes. Slope failure mechanism is mainly affected by soil strength and hydrological process within soil, the uncertainty of the soil property should also be considered in the hazard analysis. While the potential worth of loss is dependent upon landslide magnitude and is the evaluation of the landslide potential damaging impact over elements at risk. In this study we propose an integrated landslide risk assessment framework with probabilistic mechanism-driven and data-driven approach, aimed to combine different failure mechanisms of slopes in order to predict the magnitudes and potential loss of each slope under different rainfall scenarios, achieving a combination of mechanism-driven and data-driven, moving from semi-quantitative to quantitative assessment.

Methods: Firstly, By the mechanism-driven approach, stabilities of loess slopes with both translational and rotational failure mechanism were analyzed through TRIGRS and SCOOPS3D simulations incorporating unsaturated properties of loess soils. Secondly,the failure probabilities under different rainfall scenarios were estimated considering variabilities of loess geotechnical parameters in combination with the point estimate method while being mechanism driven. Then, the run-out propagation of failed slopes with different volumes and areas affected were defined through damage data produced by past landslide events, and thus values attributed to elements at risk were estimated.

Results: By the proposed landslide risk assessment approach, an empirical research was carried out at Chengguan district of Lanzhou city, a well-known thick loess terrain city in northwest of China. The results of the quantitative risk assessment show the probability of failure and specific loss of each slope, as well as the total risk of the whole area under different temporal probability. Specifically, Gaolan Mountains and Jiuzhou areas maintain a extremely high risk level spatially, with an annual property (direct cost) loss up to 18.23 million yuan. The total loss of the district are 682.86 million yuan, 1463.98 million yuan and 1782.37 million yuan for temporal probability of 0.05, 0.02 and 0.01.

Conclusions: The risk assessment framework consists of four main components: landslide stability analysis, slope failure probability analysis, run-out propagation prediction and loss estimation. The appropriate solution has been selected at each step according to its corresponding task. The applicability of this risk assessment framework is well proven in the loess areas of Lanzhou city, which provides a reference for the research and management control of regional quantitative landslide risk assessment.

SESSION 6.8

LANDSLIDES IN SUBAERIAL AND SUBAQUEOUS VOLCANIC ENVIRONMENTS

2072
NUMERICAL INVESTIGATION ON THE ROLE OF HYDROTHERMAL ALTERATION ON VOLCANIC FLANK INSTABILITIES

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Purpose: The largest landslide in recorded history happened in Mount St. Helens in May 1980 and was the trigger of a major explosive eruption (Lipman & Mullineaux, 1981). This event drew attention on the instability of volcanic edifices, and their tendency to experience lateral collapse. Indeed, volcanic lateral collapses and their associated (volcanic) debris avalanche deposits are highly destructive because of their rapid onset and ability to cause destruction across large areas. The growing structure of active volcanoes due to material addition can lead to oversteepening and overloading (McGuire, 2003). Hydrothermal activity is of particular interest as it enhances rock dissolution, promotes high pore pressures, and leads to the creation of mechanically weaker materials and promote the instability (Rattez and Veveakis, 2020). However, the effects that these processes have on volcano stability have been barely quantified (Heap and Violay, 2021), and even less modelled.

Methods: The proposed finite-element model considers the variation of the volcanic rocks mechanical properties caused by the hydrothermal alterations. It uses a stress-reduction approach and the parameters used are retrieved from experiments on rock samples from the Tutupaca volcano (Peru, 17° 01′ S, 70° 21′ W). The experimental study performed includes permeameter, uniaxial and triaxial experiments on samples retrieved by Detienne et al. (2016). The mineralogy and the microstructure of the samples have been investigated using X-ray diffraction and micro-computed tomography respectively.

Results: Two main types of alteration identified on the rocks from the Tutupaca volcano are silicic and argillic. From the mechanical experiments, it appears that the type of alteration impacts greatly the mechanical properties of a rock. Indeed, for two rocks of the same porosity and totally altered, a silicic altered rock has a plastic cap two times higher than an argillic altered one. The model predicts the safety factor of volcano flanks slopes, considering the mapping of the different alterations in the volcanic edifice. The simulation show that the safety factor is impacted by the type of alteration and its intensity.

Conclusions: To correctly model the volcanic flank instabilities, it is needed to investigate the type and intensity of alteration of the volcanic rocks and to map them accurately through the edifice.

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Keywords: volcano; landslide; hydrothermal alteration; triaxial tests; microstructure; mechanical model

MINERALOGY CONTROLS THE MECHANICAL BEHAVIOUR OF VOLCANIC SOILS SUBJECTED TO CHANGES IN WATER CONTENT

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Volcanic soils are usually regarded as soils with excellent mechanical properties. However, there is increasing evidence that slopes covered with volcanic soils are susceptible to landslide when exposed to prolonged or intense rain events. Volcanic regions are often densely populated, and the rupture of volcanic soils in mountainous areas represents a significant but poorly understood hazard. In order to improve our capacity to predict the stability of volcanic slopes subjected to rapidly changing water inputs, a better description of the hydraulic and mechanical properties, and their coupling, of volcanic soils is required. In this study, we report water retention curve, hydraulic conductivity and shear strength measurements performed on volcanic soils varying in mineralogy and microstructure. We collected undisturbed volcanic soils in Tenerife, Spain, and characterized their mineralogy by X-ray diffraction and selective chemical extractions. Soil microstructure was described based on particle size and pore size distributions as obtained from size fractionation methods (ultra-sonication, dispersion with a Na-resin) and mercury porosimetry determinations, respectively. We used state-of-the-art techniques based on the evaporation and chilled-mirror dew point methods to estimate water retention and to infer hydraulic conductivity. The mechanical behaviour of the soils with variable water content was tested by performing triaxial tests. Based on the clay-size fraction (<2 µm) mineralogy, we distinguished soils rich in allophanes (a short-range order aluminosilicate) from those dominated by halloysite (a clay mineral). The former soils have a large porosity (64%), excellent water retention (saturated gravimetric water content is about 150 %) and a saturated hydraulic conductivity of ~15mm/h. Compared to the allophanic soils, the halloysite-rich soils have a saturated gravimetric water content is nearly two times smaller, but they conduct water at low suction values (pF > 1.5) about ten times faster. The shear strength of the soils containing halloysite is higher, but comparatively more sensitive to soil moisture. Drying reduces shear strength in these soils significantly, whereas a such effect is not observed for the allophanic soils. At low water contents (pF > 3.5), pore pressure reaches high negative values, creating tensile forces that pull soil particles together, thereby increasing shear strength in the halloysitic soils. In contrats, for the allophane-rich soils, drying enhances particle aggregation, which increases inter-aggregate pore sizes and weakens soil structure and associated shear strength. This weakening could offset the increasing tensile forces due to drying, resulting in steady shear strength for allophane-rich soils. Our results, which highlight the contrasting response of shear strength to variable water content in volcanic soils differing by their secondary mineralogy, have implications for improving our capacity to model accurately the stability of slopes covered with volcanic soils.

INVENTORY OF SUBMARINE MASS-WASTING PROCESSES AT VULCANO EDIFICE (AEOLIAN ISLANDS): SPATIAL DISTRIBUTION, MORPHOMETRIC CHARACTERISTICS AND ASSOCIATED GEOHAZARD

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Insular volcanoes have generally steep flanks, characterized by a fast morphological evolution due to the interplay between volcanic, volcano-tectonic and mass-wasting processes. In this study, we show the spatial distribution and morphometric characteristics of about 450 submarine landslide scars affecting the submarine flanks of the active Vulcano volcano. The recognition and characterization of the landslide scars was realized through the analysis of high-resolution Digital Terrain Model obtained through the collection of multibeam surveys. Landslide scars occur from coastal to deep waters, even if they are mostly concentrated at or close to the edge of insular shelf and overlying submarine depositional terraces, similarly to what was observed in other insular volcanoes. Landslide scars affect areas ranging from few thousands up to hundreds of thousands of cubic meters, with slope gradients variable from 2 up to 40 degrees. The morphometry of landslide scars coupled with simple numerical model have allowed to roughly estimate the tsunamigenic potential associated with these slope failures, and the related susceptibility of the Vulcano coastline to this potential hazard. Finally, the comparison of repeated multibeam bathymetric surveys collected between 2005 and 2022 has evidenced a newly formed submarine landslide along the W flank of Vulcano. Surprisingly, no new slope failures have been detected in the same time frame in the NE submarine extension of La Fossa Caldera, where a network of gullies cutting back to the nearshore sector is present together with a strong and ongoing degassing activity, both factors potentially favouring slope instability.

MULTIDISCIPLINARY APPROACH FOR STUDYING THE FLANK INSTABILITY AT VULCANO ISLAND

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Purpose: Volcanoes are systems typically connected to a wide range of hazards, which can occur during both eruptive phases and unrests. Among these hazards, slope instability phenomena are quite frequent and, in a volcanic island, may evolve into tsunamigenic landslides. Vulcano, the southernmost volcanic island of the Aeolian archipelago (Sicily, Southern Italy), was affected during the 1988 volcanic crisis by a tsunamigenic landslide, which ran along the north-eastern flank of la Fossa cone. For this reason, the volcanic unrest occurred during the late Summer 2021 has prompted a research activity aimed to identify the potential unstable areas which can originate landslides at La Fossa cone.

Methods: This work is based on a multidisciplinary approach that relate data derived from different sources such as high-resolution topography, geological map and fieldworks. The data are combined to draft a map showing the potential source areas for flank instability phenomena. The obtained results are compared with the existing landslides cartography and InSAR data. The areas more prone to flank instability have been identified and used to derive input parameters for shallow water numerical models. The user numerical model describes the dynamics of a layer of granular material flowing downhill with a Pouliquen-Forterre rheology law. When the landslide reaches the sea, the granular layer is two-way coupled with a 3-layer model for the generation and propagation of the water waves.

Results: 13 source areas prone to landslides are individuated. They involve most of the La Fossa cone, with the exception of its south-western portion. In detail, 5 areas result to be proximal to the Vulcano Porto settlement and at least 6, located in the north-western sector, could have a tsunamigenic potential. The multilayer shallow water model produces different kind of maps and time series. For the water phase it gives the waveforms in prescribed locations and maps of arrival time, maximum water height, maximum dynamic pressure, and inundation. For the granular phase, it gives maps of maximum landslide thickness and dynamic pressure. Simulations have been performed with a maximum horizontal resolution of 2 m.

Conclusions: This work allowed to identify with high resolution the areas more exposed to flank instability at La Fossa cone. The areas are 13, distributed along the flanks, and those in the north-western sector could have a tsunamigenic potential. Numerical simulations showed that even relatively small volumes landslides can have strong impact on Volcano, due to landslide and tsunami inundation and dynamic pressure.

MONITORING AND MODELLING OF STROMBOLI VOLCANO (ITALY) REPEATED CRATER-RIM FAILURE

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Purpose: Here ground deformation measurements, geomorphological monitoring data, and 2D and 3D slope stability analyses related to the 9 October 2022 and 4 December 2022 crater-rim collapse events at Stromboli are reported. These glowing avalanches flowed down the north-western slope of the volcanic island (locally called Sciara del Fuoco) to pour into the sea.

Methods: The ground deformation monitoring was retrieved by applying the Differential Synthetic Aperture Radar (DInSAR) technique to SAR images collected by both a Ground-Based Interferometric Synthetic Aperture Radar (GB-InSAR) device and the Sentinel-1 and SAOCOM-1 space-borne SAR constellations operating at C and L band, respectively. Moreover, the topographic change detection was obtained by comparing Digital Elevation Models (DEMs) generated from Unmanned Aerial Vehicle (UAV) survey at different times (19 July 2022, 18 October 2022 and 1 February 2023). The DInSAR analysis combined with the topographic changes measurements were used to constrain and validate 3D limit equilibrium and 2D finite element analyses of slope stability, which provided insights into the nature of failure mechanisms potentially triggered by volcanic activity along the Sciara del Fuoco.

Results: The 9 October 2022 crater-rim collapse occurred after about two weeks of increasing eruptive parameters, while the 4 December 2002 occurred at the peak of the eruptive activity, characterized by frequent overflows from the crater terrace. Following the first collapse, the effusive activity, which lasted nine days, dug a canyon inside the Sciara del Fuoco to the detriment of the volcaniclastic material that constitutes the slope. Other overflows occurred in November 2022 but no failure phenomena occurred because not enough material had accumulated on the crater-rim. Differently, the collapse of 4 December 2022 involved both the crater-rim and the head of the canyon in the Sciara del Fuoco, which already showed evidence of instability from ground deformation analysis retrieved by combining ground-based and space-borne DInSAR results. The stability analyses revealed that the crater-rim sector is unstable due to the high slopes, while the collapse of the canyon head was the consequence of the debuttressing of the Sciara del Fuoco slope due to the formation of the canyon itself.

Conclusions: The results of monitoring and numerical modelling of the Stromboli crater-rim repeated failure events, at the end of 2022, allow us to state that the collapse phenomena are inevitably connected to the eruptive activity, as a factor predisposing the instability (for the accumulation of material on steep slopes) and the trigger (magma thrust on the volcaniclastic material accumulated on the crater-rim). The destabilization of part of the Sciara del Fuoco is to be considered a retrogressive effect of the formation of the canyon, also produced by the erosive action of the lava and granular flows along the slope. The approach proposed here can be generalized and applied to the instability of volcanoes characterized by persistent or semipersistent activity, where the eruptive activity is capable of accumulating volcaniclastic material on very steep slopes.

ASSESSING HAZARDS OF PYROCLASTIC AVALANCHES GENERATED BY PAROXYSMS AT STROMBOLI (ITALY)

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Purpose: The «Strombolian paroxysms» have been the most powerful explosive phenomena occurred at Stromboli (Italy) in recent centuries. The remobilization and avalanching of fresh pyroclastic deposits produced by these phenomena is relatively common. These "hot" rock avalanches, also known as deposit-derived pyroclastic density currents are usually confined to the Sciara del Fuoco, a steep depression on the northwestern side of the island. Nevertheless, during the Strombolian paroxysms in 1944, 1930, and possibly in 1906, pyroclastic avalanches occurred out of Sciara del Fuoco, flowed in the valleys on the volcano flanks, inundated regions at low elevation, and, finally, they reached the sea and produced temporary deltas. In particular, in the 1930 event, the pyroclastic avalanche reached San Vincenzo village, causing victims and damage to the buildings (see Figure1). The volume of these phenomena ranges from tens to hundreds of thousand cubic meters.

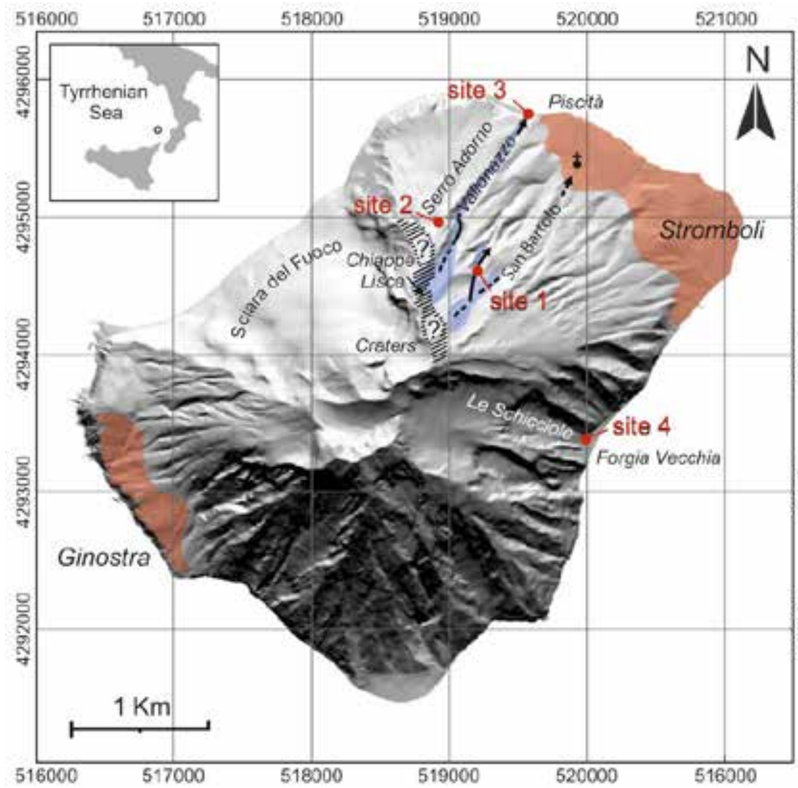

Fig. 1: Overview of 1930 PDC from Di Roberto et al., (2014). In light blue the paths of the PDC in Rittmann (1931), black arrows in Abbruzzese (1935). Possible source areas are dashed in black. Inhabitated areas are colored in orange.

Methods: In this study we perform an uncertainty quantification on the inputs and on the outputs of a 2D depth-averaged model, and a preliminary comparison with the available field data of the most recent occurrences of these phenomena. By performing Monte Carlo simulations, we test an input space varying the flow friction, the source area and thickness.

Results: Following a simplified source zonation based on the distance from the eruptive craters, we simulate pyroclastic avalanches possibly originating in all the main groups of watershed basins, where thick tephra deposits could more likely accumulate during a future paroxysm. Our tests of sensitivity highlight that the distance limits of the source area from the craters can significantly affect the invaded areas by the avalanches.

Conclusions: The maps obtained by the collapse of an axisymmetrically distributed source do not differ significantly from the envelope of those related to the examined zones. However, historical avalanches typically affected a limited number of basins, so the hazard levels conditional on a single phenomenon should be scaled appropriately - e.g. up to an order of magnitude.

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DECIPHERING CONTROLS OF SECONDARY LAHARS RELATED TO GLACIER RECESSION AND PERMAFROST DEGRADATION AT CHIMBORAZO AND COTOPAXI VOLCANO, ECUADOR

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The Ecuadorian Andes host important glacier-capped volcanoes, which are well known for their potential to trigger catastrophic syneruptive lahars. Since the last decade however, a previously unknown phenomenon of secondary lahars during dry weather is occurring on slopes of the glacierised volcanoes Cotopaxi and Chimborazo. So far, heavy precipitation has been discerned as the principal trigger of secondary lahars on Ecuadorian volcanoes, but the impact of glacier melt and permafrost degradation in response to climatic warming have only found minor consideration.

In our study, we explore the glacial- and permafrost-conditions in the source areas of the secondary lahars at Cotopaxi and Chimborazo volcano. We conducted field surveys at elevations between 4800 and 5200 masl consisting of electrical resistivity tomographies (ERT), which provide insight into the structure and conditions of the subsurface. The source area was surveyed using an unmanned aerial vehicle (UAV) equipped with a thermal infrared sensor to estimate surface temperatures and to derive information on surface properties of the debris cover and potential ice bodies below. Additionally, temperature loggers were installed for the measuring period to compare UAV derived temperatures with in-situ temperature data. Our field measurements indicate the presence of exposed ice-cored moraines, debris-covered glaciers, thermokarst depressions and relict permafrost lenses in the lahar source areas. These features are identified as potential controls of hazardous mass movements and outburst floods evolving into secondary lahars, which can be expected to emerge in deglaciating volcano flanks.

PAST AND FUTURE LANDSLIDES IN ASKJA CALDERA: SLOPE STABILITY ANALYSIS AND LINK TO CRYOSPHERIC PROCESSES

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Purpose: Askja caldera is a highly visited tourist site, which is located in a degrading permafrost area and shows morphological signs of slope instability. The latest landslide in Askja occurred in 2014 causing significant changes in the SE sector of the caldera and producing a 60-m-high tsunami wave in the caldera lake. We analyze high-resolution remote sensing data to assess slope instability at the Askja caldera walls and to reveal morphological precursors of preparing hazardous events. Along with it, we investigate a possible link between the slope processes and permafrost degradation.

Methods: In our study, we use multitemporal and multisensor high-resolution data to analyze long-term changes at Askja caldera associated with cryospheric and slope processes. We performed photogrammetric processing and comparative analysis of the 0.5-m-resolution Pleiades satellite data acquired before and after the 2014 landslide, ~1.5-m-resolution archive aerial data acquired in 1970 and 1987, and ~15-cm-resolution unmanned aerial vehicle (UAV) data collected in 2018-2022. We complement our 1970-2022 photogrammetric dataset with UAV infrared (2018-2022) and synthetic-aperture radar (SAR) data from the Sentinel-1 and TerraSAR-X satellites (2014-2022). We used Agisoft Metashape, ThermoViewer, and SARscape software to generate high-resolution digital elevation models (DEMs), extract morphometric characteristics and surface temperatures, and perform InSAR analysis of deformations at the caldera walls and adjacent slopes.

Results: Our multitemporal dataset let us investigate morphological changes at Askja caldera over 1970-2022 years and reveal evidence of degrading permafrost and slope instability such as numerous emerging thermokarst sinkholes and new cracks developed at the caldera walls. By comparison of the pre- and post-landslide DEMs (Figure 1) derived from the Pleiades data, we calculated the precise volume of the subaerial part of the 2014 landslide and investigated its morphology. We identified that the main subaerial landslide material accumulated in the middle part of the caldera wall while the surface below remained almost intact. The archive aerial dataset showed that the crown of the 2014 landslide partially matches the preexisting crack formed close to the caldera rim. Similar cracks are visible at the other areas of the caldera outer slopes adjacent to the rim. Several sectors at the rim demonstrate subsidence and can be considered as the most unstable areas. We performed morphometric analysis of such areas and estimated volumes of material that could slide down during the alleged mass wasting events. The visible optical and infrared UAV data let us investigate the fumarolic field located at the border of the 2014 landslide. The fumaroles can contribute to slope instability causing intense rock alteration and permafrost degradation.

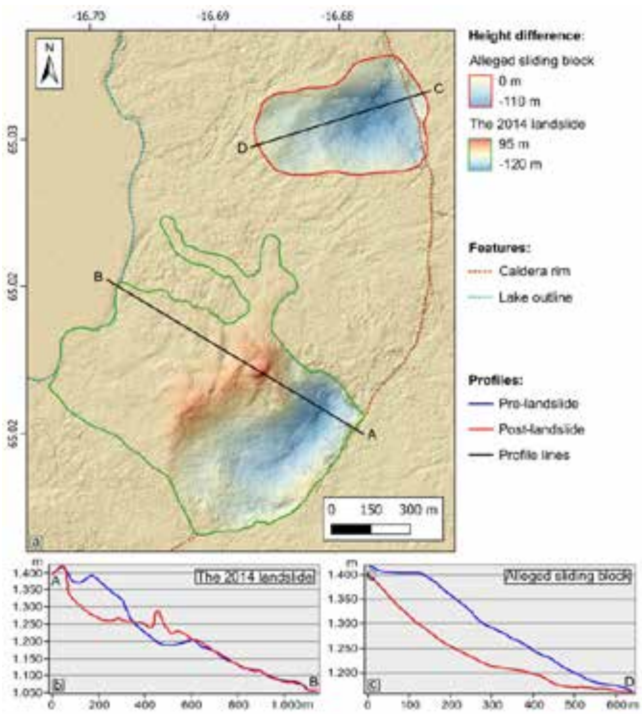

Fig. 1: Morphometric analysis of the past and possible future landslides in Askja caldera: a. Height difference map showing the result of the pre- and post-landslides DEMs comparison. b, c. Profiles representing the pre- and post-landslides topographies; the profile lines are shown in a.

Conclusions: Our results show that landslides are common in Askja caldera, and the next mass wasting can occur anytime. We suggest that the detected unstable areas should be monitored with remote sensing and on-site instrumental techniques.

LANDSLIDES LEADING TO THE DISMANTLING OF VOLCANIC EDIFICES IN THE CAMPI FLEGREI DISTRICT (SOUTHERN ITALY)

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Purpose: This work aims to describe landslide processes which are dismantling volcanic edifices of the Campi Flegrei district, in southern Italy. Research outcomes are based on the development and analysis of the CAmpi Flegrei LAndslide Geodatabase (CAFLAG), that is freely available online at https://doi.org/10.4121/14440757.v2.

Methods: The CAFLAG geodatabase refers to an area of 230 km2 including the western part of the city of Naples, and covers the time interval between 1828 and 2017. Landslides due to earthquakes, rainstorms, marine erosion or human actions affected the volcanic slopes repeatedly through time, with reports starting from the Roman period. Landslides information included within the CAFLAG geodatabase was collected from pre-existing catalogs, scientific papers, field surveys, and reports published by news websites. Where available, data on localization, date of occurrence, type of movement, volume of displaced material, impact on people and properties, predisposing and triggering factors were extracted to characterize each of the cataloged landslides. These data were associated to those of the affected sites, such as geomorphological and engineering geological properties, landslide susceptibility and hazard levels estimated by regional Basin Authorities. It is worth noting that accuracy of the site-related information was strictly dependent on the accuracy of the landslides location, which was evaluated for each event together with accuracy of temporal properties. All of the records contained in the CAFLAG geodatabase were organized in a GIS environment and geocoded in a point shapefile.

Results: The CAFLAG geodatabase encompasses 2302 landslides occurred throughout the continental and insular sectors of the Campi Flegrei area. Among them, 92% have high accurate position and 21% are characterized by temporal indications including both month and year of occurrence. The day is known for 15% of the events only. Most of the cataloged landslides are characterized by a complex movement (49%), mainly combining flow and slide mechanisms. Among the non-complex landslides, the most recurrent movement type is fall (25%), which is slightly more frequent than slide and flow (13% each). Volumetric data are available for 277 landslides. Values range from 1 to 7.500 m3, with a mean of about 123 m3 per event. About 40% of the 277 landslides displaced a volume lower or equal to 10 m3, and 23 % a volume higher or equal to 100 m3. Peaks of landslides result in the years 1986, 1997, 2005 (i.e. 50, 91, 70 events, respectively), exceeding significantly the average value of 2.4 events per year. The highest concentration of landslides is along the coastal sector, confirming the strongly active coastal dynamics in the area.

Conclusions: In volcanic landscapes, landslide catalogs are even more necessary to reach a comprehensive knowledge about the role played by mass movements in the geomorphic evolution of these settings, and on processes that lead to slope failures and control their spatial variations. Therefore, landslides cataloged within the CAFLAG geodatabase provide a valuable opportunity to investigate the occurrence of landslides in relation to other geo-environmental predisposing or triggering factors in the Campi Flegrei area, as well as to assess the widespread landslide hazard conditions.

SESSION 2.5

GEOPHYSICAL IMAGING, CLOSE-RANGE SENSING AND GEOMODELLING OF LANDSLIDE PROCESSES

LANDSLIDES LIVE IN 3D: 3 CASES ILLUSTRATING WHY 3D GEOPHYSICS IS NEEDED

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Purpose: Landslides can develop into a very wide range of landforms varying in shape, size and character. What is common for all types, however, is that they always form a 3D body, on which any surface observation can only bring partial information. Therefore, geophysical methods are commonly used to study the internal structure of the landslides. However, most of the geophysical methods are applied in vertical cross-sections. There are few exceptions, but these applications have usually very limited depth and/or areal range. This is a problem for obtaining of information on 3D structure of the landslide body, necessary to understand its formation, causes, triggers and potential further activity. Additionally, some landslide-prone environments are anisotropic, and the results depend on the relative orientation of the cross-section to the structures.

Methods: The easiest solution is to measure multiple 2D ERT profiles, designed to cover the whole studied landslide, convert all profiles into unique scale and visualise the results in a 3D environment software, such as AutoCAD, MOVE, or SketchUp. In the cases where dense and evenly distributed data are available, it is possible to interpolate the inverted data into a real 3D space in a specialized software such as Voxler 2. Finally, a combination of various methods can be applied, providing they are based upon similar physical principles, but using different collection geometry. For example, it is possible to combine the EMC (with dense parallel profiles covering the horizontal plane, but with shallow depth reach) and ERT (with vertical cross-sections spread across the study area).

Results: First presented case study concerns investigation of potential instability at the proposed road bypass of Svor (N. Bohemia). The bedrock is formed by anisotropic layers of clays and sandstones, and 3D visualization of 12 ERT profiles, covering the studied slope, allowed to observe the shallow reach of the landslides and ruled out any deeper block type slope deformations. The construction of a new highway segment at Bělotín (N Moravia) was stopped due to supposed acceleration of a landslide. A combination of the EMC and ERT survey was performed to visualise the situation including the 3D morphology of the slope and its underground. The 3D analyses allowed to conclude that the site is not endangered and the roadworks could be renewed. The third case study is a landslide-affected slope at Hořetice (NW Bohemia), recently reactivated due to seeping of water from a nearby sludge pit through inclined layers of alternating sands and clays. The 3D analysis combining the EMC and ERT was performed, as well as 3D interpolation of data from 12 ERT profiles across whole site. The 3D imaging helped to understand the position and dip of the permeable sandy layers.

Conclusions: We conclude that the 3D visualisation and processing of the geophysical data can bring new insights into understanding the spatial composition of the geological environment, and allows to observe underground structures in the landslides. The contribution illustrates this on three case studies of various types of landslides using geophysical methods, where classic 2D cross-sections are not revealing enough.

GEOPHYSICAL CHARACTERISATION AND GEOMODELLING OF THE GIANT SAN ANDRES LANDSLIDE, EL HIERRO ISLAND, SPAIN

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Purpose: The article presents new prospection results obtained for the incipient San Andrés landslide on the El Hierro (Canary Islands, Spain) island, which represents a giant instability of this volcanic island and thus belongs to the largest known mass movements on Earth.

Methods: The research combines multiple geophysical measurement techniques (active and passive) complemented by remotely sensed (UAV) surveys to characterize rock properties inside and outside the landslide area. The complexity of multiple geophysical and geological outputs has been approached by presenting results within a multi-scale 3D geomodel. Active seismic data along profiles were processed by the multichannel analysis of surface waves and as seismic refraction tomography profiles to determine, respectively, the S- and P-wave velocity distribution over depth. The ambient noise records collected by seismological arrays and along single-station profiles were processed by surface wave inversion (only within the arrays) and by the horizontal-to-vertical spectral ratio analysis for the near-surface stratigraphy. The latter allowed us to assess the local fundamental frequency of shaking and this way to estimate the thickness of the softer surface layer under the seismic station.

Results: The geophysical data identified several significant contrasts, the first at a depth of about 30-50 m, below highly fractured surficial rocks, where still softer rocks can be found (marked by a shear-wave velocity of 1000 to 2000 m/s) ; very hard rocks with shear-wave velocities larger than 2000 m/s could be found at larger depths (>> 100 m). Our results further suggest that the failure surface has a planar geometry near the scarp and at shallow depths; its form is more uncertain (but probably curved) below, down to the estimated maximum depth of 320 m in the northeastern part and to 420 m in the southwestern part. The interpretation of the ambient noise readings further suggests similar rock properties inside and outside of the mass movement. Additionally, the prospection showed that strength properties of the rocks may vary significantly even over relatively short distances (several hundreds of meters).

Conclusions: The geophysical investigation of the San Andrés mega-landslide revealed new details about its internal structure and volcanic rock properties outside and inside its on-shore limits. Indeed, the geophysical results provided new evidences about the existence and geometry of a continuous sliding plane (maximum depth of 300 - 420 m); this is an important step toward the better understanding of the present stability conditions of the landslide. Similar rock properties found inside and outside the mass movement further suggest that its previous catastrophically fast movement did not affect bulk properties of the transported rocks as it chiefly occurred along the weakened plane forming the main steep scarp on the surface. The collected data visualized in the 3D geological mode form the basis for the preparation of a geotechnical model (including also inputs from geotechnical tests completed recently), which could be used to compute slope stability and simulate slope deformation over the San Andrés landslide. Modelling and simulations are now planned to be carried out for multiple failure scenarios.

NEW INSIGHTS ON A SLOW-MOVING LANDSLIDE FROM A MULTI-METHOD GEOPHYSICAL INVESTIGATION (HEINZENBERG, SWITZERLAND)

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Purpose

The effect of water on landslide movement is well known and refilling a drained lake within a long-known slow-moving landslide might reactivate movements. The Heinzenberg Landslide is known for more than 200 years and mitigation measures like torrent control and drainage of a lake have proved to successfully slow down movements from 0.25 m/a (geodetically measured 1910-1931) to 0.04 m/a in 2017. We conducted a large short-term seismic experiment to characterize the internal structure and seismic response of different compartments within the Heinzenberg slope (Figure 1a-c). Results of this experiment serve as a baseline model for future analyses of the changing stability and seismic response of the slope monitored by a permanently installed seismic station close to the refilled lake (Lake Lüsch).

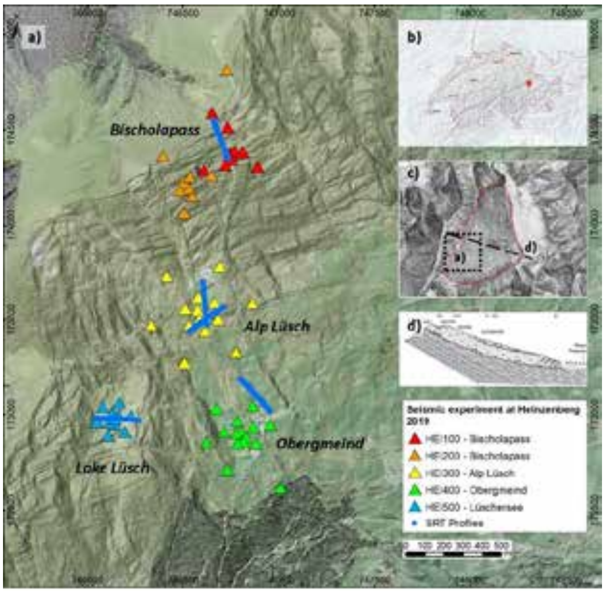

Fig. 1: Installation and array setup of the seismic experiment at Heinzenberg. a) The five seismic refraction tomography profiles (blue lines) and the passive seismic array setups at Heinzenberg; b) Location of the Heinzenberg Landslide in Switzerland; c) Digital elevation model of the Heinzenberg surroundings with the landslide area marked in red, the area of a) highlighted and the cross-section of d); d) Sketch of a geologic cross-section through Heinzenberg inferred from the seismic campaign and the geologic map of Switzerland.

Methods: Previous monitoring of the Heinzenberg Landslide focused on surface displacement measurements. We complemented these measurements with seismological techniques on selected sites, namely the acquisition of ambient vibration data for H/V analysis, polarization analysis, site-to-reference spectral ratios, surface wave analysis with array methods, seismic refraction tomography and multichannel analysis of surface waves. These methods allow an understanding of the subsurface conditions in terms of shear-wave velocity profiles, partial volumes, the orientation of fractures, and the different depths of interlayers.

Results: Seismic data from our experiment give us insights into the landslide structure. Close to the ridge at Bischolapass and former Lake Lüsch we find the rock mass of a deep-seated gravitational slope deformation (DSGSD) reaching a depth of more than 60 m. At Alp Lüsch and Obergmeind shallow secondary landslides with about 30 m thickness cover the DSGSD, below which the intact bedrock is detected at a depth of around 76 m. The results show that ambient vibration analysis ouptuts compare well with those of active seismic methods. Several geophysical sections and 1D shear-wave velocity logs could be established to characterize the seismic response of the different prospected compartments.

Conclusions: The Heinzenberg Landslide shows a typical picture of a DSGSD with a double ridge (mountain splitting) and uphill-facing scarps at the crest of the slope. Tensional cracks and other extensional features as well as a flattening of the possible sliding surface (interlayer) characterize the middle part of the landslide as it was detected during the analysis of seismic data. In this area also the existence of different shallow secondary slides are tracked and give an additional insight into the Heinzenberg Landslide (Figure 1d). The application of seismic methods complemented the information about these geomorphic features and from geodetic measurements by providing a deeper understanding of the internal structure of the Heinzenberg Landslide.

MULTI-DISCIPLINARY INVESTIGATION TO CHARACTERIZE AND REMEDIATE A COMPLEX HISTORIC LANDSLIDE IN BRITISH COLUMBIA, CANADA

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Purpose: The Thompson River Valley rail corridor, located west of Kamloops, British Columbia, forms a vital transport link for both of Canada's primary rail operators, Canadian Pacific (CP) and Canadian National (CN). A high concentration of landslides between Ashcroft and Spences Bridge has posed a threat to railway infrastructure since the railways were built over 100 years ago. These landslides have the potential to cut off the flow of goods between Canada's busiest container port, the Port of Vancouver, and the rest of inland Canada. Periodic reactivation and slow displacement rates of these historic landslides result in slow travel orders and frequent maintenance, creating a bottleneck for rail traffic that passes through the corridor. One of the more recent and active landslide reactivations has occurred along the riverbank of the massive (15 Mm3) North Slide that originally failed in October 1880, temporarily blocking the Thompson River.

Methods: A multi-disciplinary approach, involving hydrology, geotechnics, geology, and geophysics was initiated to investigate the primary landslide mechanisms and reasons for retrogression. Riverbank erosion has steadily progressed in the past 100 years based on estimates from aerial photography and satellite imagery. Recent field work, carried out in collaboration with the Geological Survey of Canada (GSC), has expanded on previous knowledge of the site and focused on identifying remedial solutions to minimize future displacement. In the past year, field work has focused on several aspects contributing to displacement. Work has consisted of 1) updated river bathymetry to pinpoint changes due to river scour; 2) high resolution imagery surveys (UAV photogrammetry and LiDAR) of the entire slide mass to detect change and develop a digital elevation model for stability analysis; and 3) geophysics (electrical resistivity tomography, seismic refraction, multichannel analysis of surface waves, and passive seismic velocity models) to identify potential stratigraphic boundaries and sub-surface formations.

Results: Preliminary results from the site investigation indicate advancing riverbank erosion adjacent to North Slide. Change detection analysis shows settlement focused in a particularly active area of retrogression. Information obtained from the geophysics program identified possible slump blocks and groundwater shortcutting through the historical landslide debris. Active outflow is observed year-round near the landslide toe. The results of the preliminary investigation will be used to guide the upcoming geotechnical investigation at North Slide.

Conclusions: The North Slide is a complex landslide with years of historical records and study. The present goal of the site investigation is to incorporate previous knowledge and bridge the gap with new methods, moving towards a practical and long-term solution for the railway.

GEOPHYSICAL SURVEY FOR THE ESTIMATION OF GEOTECHNICAL PARAMETERS AND FOR THE STABILITY ASSESSMENT OF THE THEILLY LANDSLIDE (VDA, ITALY)

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Purpose: An efficient stability analysis is closely linked to a good assignment of geotechnical parameters to the strata identified in the construction of the geological model. However, it is not always possible to determine the geotechnical parameters from direct tests, but there are indirect methods in the literature for determining the main geotechnical parameters of the ground using seismic parameters such as seismic velocities. Numerous correlations exist in the literature between shear wave velocity (VS), and the N-SPT value derived from penetrometric tests. This paper presents the geotechnical model of the Theilly landslide (Western Alps, Italy) obtained by integrating the results of a multi-parameter geophysical survey (H/V seismic noise and ground-penetrating radar) with stratigraphic and geomorphologic observations, digital terrain model and field survey data. In particular, it is shown how VS values can be related to values obtained from direct tests such as N-SPT and, using the direct or estimated N-SPT value, it is possible to directly derive the friction angle value (ϕ'). Although, the indirect estimation of N-SPT is subject to a higher level of error, it could be very useful in the early stages of an emergency, when direct data are not available, and a preliminary forward and backward stability analysis could be performed to assess landslide evolution and civil protection actions.

Methods: Geophysical surveys were conducted on the landslide body and on nearby locations. The H/V survey identified the presence of 2 discontinuity surfaces and thus the presence of 3 seismo-layers. The GPR survey allowed the surface portion of the slope to be studied, identifying an extremely heterogeneous debris layer. The H/V data allowed the interface depth to be related to the frequency of the identified peaks and the VS of the identified seismic layers. It was then possible to apply empirical equations to derive the value of N-SPT, and consequently ϕ', from the VS obtained through the H/V measurements.

Results: The geotechnical parameters obtained from geophysical and direct tests were used to create a geotechnical model of the landslide to perform a reliable stability analysis. The analysis of the triggering conditions of the landslide was conducted through hydrologic-geotechnical modelling, evaluating the behaviour of the slope under different rainfall scenarios, and considering the stabilization interventions present on the slope. The results of the filtration analyses showed a top-down saturation mechanism, which resulted in the generation of positive pore water pressure in the first few meters of soil and the formation of a saturated front with a maximum thickness of 5 m. Stability analyses conducted for the same events showed the development of a shallow landslide affecting the first few meters of saturated soil.

Conclusions: The geotechnical parameters estimated from the geophysical tests are in agreement with the data from the direct tests and have made it possible to create a geotechnical model that is faithful to reality. The modelling results are compatible with the actual evolution of the phenomenon and have provided insight into the triggering mechanism, providing models to support future interventions.

INVESTIGATING THE INFLUENCE OF FRACTURES AND NEAR-SURFACE TEMPERATURE VARIATIONS ON THE STABILITY OF A SEA ARCH THROUGH AMBIENT VIBRATION MONITORING AND NUMERICAL MODAL ANALYSIS

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Purpose: Structural health monitoring of cultural- or natural-heritage landforms is paramount for their conservation and management. In this context, understanding the role of preparatory and geological predisposing factors in impacting their stability is crucial for defining reliable conservation strategies. In this work, we present results from ambient vibration measurements and 3D finite-element numerical modal analysis to characterize the dynamic behavior of the Wied Il-Mielah coastal arch (Maltese Archipelago). This remarkable landmark represents a natural heritage site of Gozo and is one of the last remaining coastal arches on the island after collapse of the Azure Window in 2017. Persistent joints and continuous environmental stresses make this site an ideal case for investigating the interaction between rock mass fractures, near-surface temperature fluctuations, and their influence on the long-term stability of the arch.

Methods: Modal properties of the arch were investigated using a combination of geophysical monitoring and numerical modeling techniques. During daily surveys with seasonal recurrence, ambient vibration measurements were performed using a geophone array deployed along the arch length. Spectral and frequency-dependent polarization processing and cross-correlation modal analysis were conducted on the array-based dataset to identify resonance frequencies and polarization attributes, characterize the mode shapes, and study potential temperature-induced frequency shifts through continuous frequency tracking and cross-correlation. 3D finite-element numerical modal analysis was also conducted to predict vibrational modes and compare against field data. Two different models were implemented to test the hypothesis of a fracture-control on the dynamic behavior of the arch. The first model assumed an isotropic and homogeneous material, while the second included a main joint as a zone of reduced modulus. Modeled resonance frequencies and relative modal displacements were extracted for each of the two implemented models to compare numerical results with field data.

Results: Spectral analysis of ambient vibrations revealed two resonance frequencies at each array station. The polarization attributes for these two modes allowed us to interpret them as first-order bending modes. However, modal vectors show a complex distribution along the arch length that might depend on the presence of fractures dividing the structure into adjacent compartments. Cross-correlation modal analysis confirmed this evidence describing an identical distribution of relative modal displacements. Frequency tracking highlighted a direct and almost zero-lag correlation between daily temperature changes and frequency variations, suggesting that stress stiffening is the primary mechanism controlling the observed drifts. In contrast, an inverse correlation with a 1-month lag was observed at the seasonal scale. This result was interpreted as caused by rock mass thermal dilation and contraction causing fractures to open and close, thus determining a delayed and periodic variation in rock mass stiffness. A successful match between field data and model results was achieved only for the model containing the simplified fracture. Modeled resonance frequencies match measured values to within 10%, and the associated modal vectors replicated results of cross-correlation modal analysis. The fully isotropic model did not match field data, highlighting how homogeneous models may fail to simulate the dynamic behavior of jointed rock structures.

Conclusions: By combining array-based ambient vibration measurements and 3D finite-element numerical modal analysis, this study provides an improved understanding of the role of structurally-relevant joints and near-surface temperature variations on the stability of natural rock landforms.

INTEGRATED FOUR-YEAR TIME-LAPSE GEOPHYSICAL IMAGING WITH ESTIMATED UNCERTAINTY OF A LANDSLIDE PRONE TO THE ANTHROPOLOGICAL TRIGGERING - AN EXAMPLE FROM OUTER CARPATHIANS

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Purpose: The problem of landslide formation has been growing in recent years, especially in cases where human influence is essential. Increasing urbanization and commercialization of mountain areas, along with ongoing climate change, are intensifying the activity of previously stable, or slowly sliding slopes. One area especially susceptible to such phenomena is the Outer Western Carpathians. In particular, the mountainous area of the Beskids (southern Poland), whose peculiar geological structure (Carpathian flysch) makes it highly prone to landslides, is currently undergoing intensive settlement, with the additional observation of a change in precipitation characteristics. One example is the landslide in the village of Cisiec (Żywiec Beskids), where the complex evolution of both natural processes and human activity provides an exquisite example for studying such phenomena in a situation where the influence of individual triggers can be determined.

Methods: In order to visualize the changes taking place inside the landslide structure, a multi-method approach integrating both passive (seismological monitoring) and active seismic (reflection imaging, refraction tomography, analysis of surface waves), as well as electrical resistivity and magnetic methods is crucial. In addition, remote sensing methods were used for accurate surface reconnaissance of the study area. The integration of techniques during processing stage, made it possible to determine the uncertainty of the result, such an indispensable parameter for estimating whether a phenomenon is actually occurring or whether it is the result of a measurement methodology. The final data classification by machine learning approach allowed to distinguish most active parts of the study site.

Results: As a result of the observations, it was possible to specify the way the landslide is evolving in individual parts of the year, as well as determining the total magnitude of annual changes. Based on the analysis of the collected data, the landslide is classified as a slow-developing one, with quite varied behavior in both winter (the greatest influence of environmental factors) and summer. Particularly evident is the impact of artificial snow, resulting from the use of the area as a ski slope in winter.

Conclusions: Integrated, four-year imaging of the landslide area in the village of Cisiec, provided interesting information on how similar cases may develop in the Beskid Mountains. The progressive urbanization of the Carpathian area means that similar situations are becoming more frequent. Increasing human influence on the environment, along with climate change, is causing greater landslide susceptibility of the area, with distinctly different seasonal characteristics. The collected data and experience can be a reference for further research on this issue in similar cases. Thus, the dataset will be open on Episodes platform in 2024.

JOINT P-WAVE AND S-WAVE SEISMIC REFRACTION TOMOGRAPHY SURVEY FOR LANDSLIDE AREA INVESTIGATIONS

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Purpose: Landslides in Poland occur commonly and are set in wide range of geological situations. The most extensive landslides are developing in the Carpathian mountains composed of landslide-prone Cenozoic flysh rocks. Commonly occurring landslides in Quaternary glacial deposits are widespread across virtually whole area of lowlands. Although these landslides are relatively small and confined to steep slopes, they sometimes affect urbanized areas. Other, atypical landslides e.g. structurally controlled are spatially limited and context dependant. Polish geological survey is commonly asked for evaluation of landslide sites and risk assessment, and thus the need for fast investigative tools for landslide imaging is needed.

Methods: In our experience the shallow seismic survey yielding P wave and S wave is the most suitable for the rapid landslide investigations, especially on the landslides, that are still active. The analysis of the velocity fields usually allows for delineation of the slide surface, but also reveal details of intact massive structure and minute changes in composition/water content of sliding mass. The imaging of both P wave and S wave is crucial because both waves react to different medium parameters – mostly density for P wave and mechanical parameters for S wave. Joint imaging of both velocity fields carry huge synergy in subsurface understanding. In our investigations we apply standardized seismic technique – seismic refraction tomography, with spatial oversampling. The survey for each wave type is done consecutively along the same line, with use of vertical and horizontal geophones respectively for P and S wave. Sledgehammer usually provides sufficient energy for the survey. Simple custom-made anvil is used for S wave generation in horizontal plane. Executing P and S surveys along the same line allows us to regard the obtained cross sections as spatially analogous and compute small strain moduli and Poisson ratio fields (cross sections) that facilitate the interpretations.

Results: The figure 1 presents an example of axial cross sections obtained for the landslide, where clays covering granite massif are forming the creeping mass. Note, that high velocity area close to the middle of the P section are in fact incorporated into soft sediments (as illustrated by its relatively low S velocity), and might be prone to mass movement.

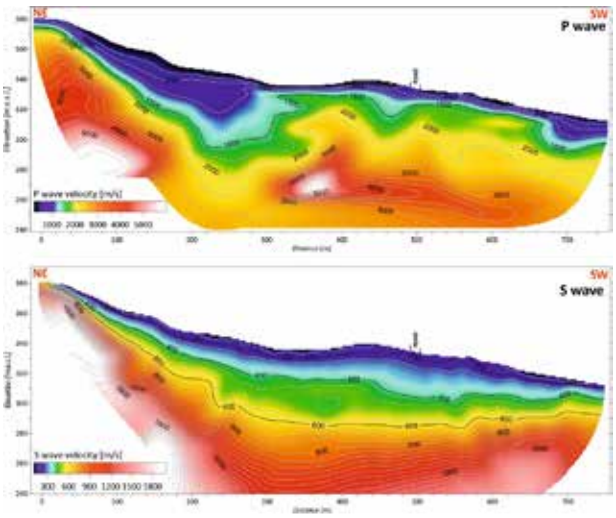

Fig. 1: Seismic cross sections for P wave (top) and S wave (bottom).
Landslide area Siedlecin, SW Poland.

Conclusions: The joint survey of P wave and S wave seismic refraction tomography is in our experience the most useful geophysical toolbox for imaging and understanding of the geology of landslide areas. Obtaining S wave velocity field is crucial, especially in soft sediment settings, where P wave velocity field alone is usually ambiguous. Other seismic techniques were tested for obtaining reliable velocity fields. The commonly used multichannel analysis of surface waves (MASW) tend to yield results too shallow to be considered useful, while velocity fields obtained by refraction profiling are lacking in resolution. Reflection seismic never yielded any useful images for the purpose of landslide investigations in our experience.

IMPROVING SELF-POTENTIAL METHODOLOGY FOR A BETTER UNDERSTANDING OF SUBSURFACE FLOW PATTERNS IN AN ACTIVE LANDSLIDE

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The Self-Potential (SP) method is a geoelectrical technique that can detect subsurface fluid flows. However, it has been limited in its systematic use due to insufficient theoretical background and limitations in data interpretation, so far. Deep Electrical Resistivity Tomography (DERT) surveys have enabled the collection of numerous electrical resistivity data sets, which has facilitated the development of multichannel and distributed systems capable of a continuous sampling of electrical potentials using multiple electrode couples inserted into the ground (Bocchia et al., 2021). As a result, the effectiveness of using DERT methods to enhance the SP method is increasingly recognized. Despite these noticeable improvements, there are still challenges in conducting and retrieving SP signals from DERT surveys. In addition, SP signals are usually considered noise in ERT models and for this reason they are often filtered. We propose a new approach to conduct and retrieve SP signals from DERT surveys to outline subsurface flow patterns in an active landslide. The approach involves a new-concept Resistivity Distributed System, such as the Fullwaver system (MPT-IRIS — www. iris-instrument.com), which is capable of logging both artificial and self-potentials at a frequency of 100 Hz between multiple pairs of electrodes. We also propose a practical approach to retrieve SP signals from 3D-DERT data using uncommon array techniques similar to the traditional Gradient or leap-frog technique. In this work, we conducted a 3D-DERT survey in 2 consecutive days to study an active landslide located in the Carnic Alps. We were able to identify useful SP signals from the data loggers, which we processed using specific procedures for the creation of time-lapse SP maps. The retrieved SP signals exhibit a good repeatability and stability in time, which make it very helpful in time-lapse landslide monitoring. In time-lapse mapping, typical patterns could be recognized and spatially correlated, allowing for a deeper understanding of groundwater flow dynamics. In addition, we inferred flow pathways from the surface by assuming that the coarse materials carried into the landslide provide a preferential flow due to their high permeability. Our analysis shows that the SP signals collected using the proposed data loggers can be effectively identified and processed, even when stainless-steel electrodes are used in place of non-polarizing electrodes. Our approach can help identify areas of potential interest for landslide monitoring from a qualitative perspective. The combination of DERT and SP methods can improve the ability to accurately detect and monitor subsurface fluid flows, even under complex geological conditions. We plan to apply these procedures to other areas to enhance the understanding of groundwater flow dynamics and to improve landslide monitoring.

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COMPREHENSIVE ELECTRICAL IMAGING OF THE RIDGE BELOW THE ANCIENT CHURCH OF SAINT MARTIN (DOLOMITES, ITALY)

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Purpose: Electrical methods proved to be powerful tools for imaging and monitoring active landslides (Supper et al., 2014). We report here about a comprehensive electrical survey conducted to image the structure and stratigrapy of the ridge below the St. Martin church in Valle di Cadore (Dolomites, Italy). Site geology is fairly complicated as the ridge is sandwiched between two major thrusts (Figure 1): the Valsugana line (VL) and the Boite line (BL), the former detaching the entire stratigraphic sequence of the Dolomites down to the crystalline basement. A deep-seated landslide is affecting the southern slope of the St. Martin ridge (Figure 1b). The southern slope is lowering at a rate of about 0.5-1.0 m/yr and the movement occurs along an almost vertical discontinuity.

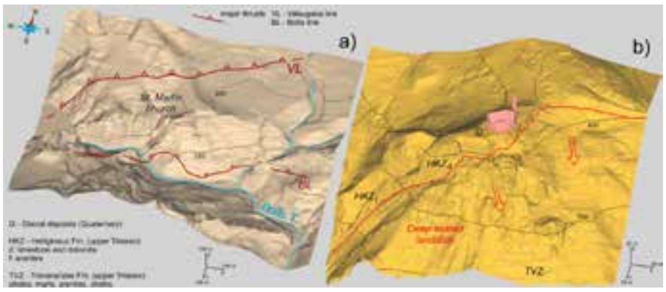

Fig. 1: (a) Digital terrain model of the lower Boite valley showing major geological thrusts. (b) Detailed view of the ridge and of the St. Martin church.

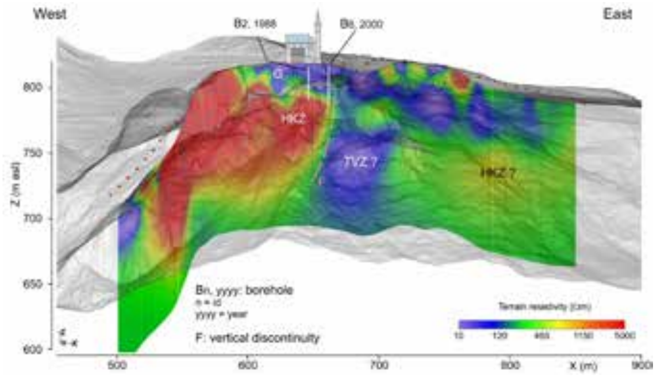

Fig. 2: West-east section extracted from the 3D resistivity model obtained via joint/constrained inversion. B2 and B6 are boreholes drilled before the geophysical survey.

Methods: The site was investigated, targeting the stiff bedrock (HKZd), using several different electrical methods and technologies using 3D geometry: the new-generation FullWaver (Gance et al., 2018); the novel-concept Multisource (LaBrecque et al., 2013); the complex-conductivity (Flores Orozco et al., 2019) as well as the multi-electrode technique.

Results and conclusions: Preliminary inversion was not successful as the electrical field was severely distorted because of the several tens of steel-cased micropiles (as deep as 20 m) located below the church foundation. Some of the model cells were poorly determined resulting biased by the initial model (fairly resistive). This led to wrong assumptions on the target depth to the north of the church. A specific inversion had to be then designed to cope with this problem. Some seismic constraints (near surface longitudinal and shear wave velocities) were added to the initial model to tune the inversion parameters and finally obtain a reliable resistivity volume (Figure 2). A major discontinuity, either a fault or a deeply incised glacial valley, was imaged to the west of the church. Geophysical interpretation was validated using five new boreholes (> 50 m of depth) drilled to assist the design of the church reinforcement.

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INTEGRATION OF MULTISOURCE SURVEYS IN A THREE-DIMENSIONAL SOFTWARE ENVIRONMENT FOR THE SUBSURFACE CHARACTERIZATION OF A DEEP-SEATED SLOW-MOVING ROCKSLIDE

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Purpose: Subsurface characterization is a crucial step in the investigation of large deep-seated landslides. It is undertaken whenever possible to address relevant, site-specific dynamics at slope scale, or to provide support to stability analyses and physically based numerical modelling. Nowadays, it is widespread practice to integrate traditional borehole investigation either with geophysical surveys or topographical and remote sensing-derived monitoring datasets. However, only few studies have focused on the integration of multisource surveys datasets and rely mostly on distributed, indirect information provided by geophysics. This note deals with the use of three-dimensional software environment for the characterization of a deep-seated slow-moving rockslide in the Isarco valley (South Tyrol) for which a significant amount of sub-surface investigation data are available and can be analysed with respect, also, to surface morphologic and monitoring data.

Methods: This work is based on the integration in three-dimensional software environment (MOVE, Petroleum Experts) of data from 44 borehole drillings, 27 inclinometer casings, more than 10 km of DC resistivity tomography and 7 km of seismic refraction profiles, space-borne interferometric archive and open-source data, robotic total station monitoring data of a viaduct piers affected by the landslide, LiDAR-derived elevation model. Data integration for subsurface characterization was performed in several steps, starting from morphological mapping supported by detailed elevation models and interferometric data in GIS environment to the sub-surface expression of surface morphologies constrained by boreholes logs, geophysics, inclinometric and topographical displacements record in three-dimensional software environment.

Results: The resulting 3D subsurface model of the landslides allows key longitudinal cross-sections to be extracted describing the kinematic and geological model of the rockslide, which can also be the basis for the analysis of the relationships between long-term displacement records and hydrogeological and meteorological data by the means of numerical modelling.

Conclusions: Three-dimensional data integration is a promising way to detect/evaluate inconsistences between the datasets involved, and, supposedly, to raise doubts through which pursue a wider perspective regarding the instability phenomenon.

SESSION 6.1

ADVANCES IN UNDERSTANDING AND MODELLING THE INTERNAL AND SURFACE DEFORMATION OF LANDSLIDES (part I)

THE IMPORTANCE OF INTERNAL DEFORMATION IN LANDSLIDES AND ROCK SLOPE FAILURES

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Most landslides and rock slope failures incorporate a significant degree of internal deformation although this is rarely considered in conventional slope stability analyses. The amount and type of internal deformation is inherently related to many factors including the slope failure kinematics/mechanism, the rock mass characteristics, groundwater and weathering.

This paper will draw on extensive collaborative landslide/rock slope research conducted in North America and Europe; it will include observations on major landslides, civil engineering and open pit mine slopes. A combined state-of-the-art approach will be presented for investigating internal slope internal deformation involving field and remote sensing characterization- numerical modelling and slope monitoring.

We will attempt to show that internal slope deformation may be both multi-scale and multi-temporal in nature. Considering scale, slope internal deformation may occur from the microcrack scale to the local scale (joint/crack propagation/failure surface dilation/degradation) and to the global slope scale (e.g. active-passive block transition, toe heave/breakout). Considering the role of time, internal deformation may occur within a slope rapidly, in a brittle manner (e.g. when localized along adverse dipping discontinuities) or progressively over a wide range of time vary from engineering time to 1000's of years in the case of post-glacial slopes.

The relationship between slope internal deformation and the rock mass characteristics is discussed with reference to case histories and it is suggested that the scale and nature of slope internal deformation is strongly related to the GSI (blockiness and joint conditions) and also to the block shape/number, and joint connectivity of the rock mass fracture network.

The relationship between the slope kinematics/failure mechanism and internal deformation will be discussed focusing on the importance of block theory and considering slope failures with respect to the topology of the blocks comprising the landslide. The location of the internal damage within a slope is fundamental and may result in changes in the slope kinematic constraints over time. The potential role of progressive weathering and groundwater pressures on internal deformation is also considered.

Finally, the importance of considering the relationships between observed external surface slope deformation/deformation features and internal slope deformation will be addressed and recommendations made for improving our knowledge and understanding of internal slope deformation.

SLOPE PROCESSES AND LARGE-SCALE INFRASTRUCTURES: THE VARNA LANDSLIDE ALONG THE ACCESS TO THE BRENNER BASE TUNNEL (ISARCO VALLEY, NORTHERN ITALIAN ALPS)

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Purpose: The Varna landslide accumulation, located in the northern Alps (Italy), it was studied as a part of Forch service tunnel project; this tunnel is a segment of the southern access to the Brenner base railway tunnel, along the right side, facing east, of the Isarco Valley.

Methods: The collapsed slope is characterized by debris deposits generated by weathering of the heavily jointed phyllitic rock mass that outcrops in the upper part of the slope itself. The aim of the study consists in the geological and geomorphological characterization of the landslide accumulation and evaluation of its state of activity. The area was subjected to detailed geological and geomorphological field surveys supported by the analysis of several continuous core boreholes (maximum depth 360 m), magneto-telluric survey, electrical and seismic (P and S waves) tomographies. Furthermore, the analysis of interferometric data of the COSMO-SkyMed satellite constellation in the years 2011-14 was carried out.

Results: A landslide accumulation of about 85 ha extending between 670 m and about 1,400 m a.s.l. was mapped. The factors predisposing to the slope instability have been identified in a series of fault systems (ENE-WSW and NW-SE) and by the orientation of the shear band cleavage (SC') within the phyllites. The borehole drilled in the central area of the landslide (1025 m a.s.l.) showed the presence of a 200 m thick brecciated deposit (from 0 to 240 m), containing portions of highly fractured rock, overlying a clayey layer about 2 m thick. The geophysical investigations, in particular the magneto-telluric stations, have made it possible to define the geometry of the landslide accumulation. The remaining boreholes made it possible to evaluate the stratigraphic relationships of the landslide with the alluvial and glacial deposits in the Isarco valley floor. Moreover, the analysis of the interferometric data confirmed that the landslide is currently inactive; however, slow and shallow movements affect the talus in some sectors along the slope.

Conclusions: The study allowed the geometries and the state of activity of the Varna landslide accumulation to be defined, along with its relative age. The foot of the landslide was reworked during the Last Glacial Maximum (>30 ka BP) and covered by late Quaternary glacial and alluvial deposits. Therefore, the onset of the rock slide occurred before the Last Glacial Maximum. From the analysis of the available data, and based on the features of the Quaternary deposits covering the foot of the landslide, it is possible to define its state of activity as relict. Given the results of geological and geophysical investigations, the tunnel has been considered as feasible and will be excavated in the northern portion of the landslide accumulation for about 100 m.

ASSESSING THE IMPACT OF RESERVOIR DRAWDOWN ON A DEEP-SEATED LANDSLIDE IN WESTERN ALBERTA

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Purpose: Several slopes in the plains of western Canada are mainly composed of glacial moraine (till materials), which overlays sedimentary rocks consisting of alternating layers of clayey siltstones, coal shales, mudstone, and sandstone. While some of these slopes have remained stable for centuries and will likely continue to be stable, others have become unstable due to a combination of two primary triggers: human activities, such as construction, as well as the presence of weak layers within the sedimentary rocks, such as the coal shales. An example is the Chin Coulee landslide located in southern Alberta, specifically at the north slope of the Chin Reservoir which has experienced movements since 1980. The instability is believed to be triggered by a combination of factors including highway 36 situated at the landslide headscarp, rainfall, the reservoir water level, and a coal layer in which the landslide is seated. All these factors pose risks to the highway and any downstream infrastructure in the case of reservoir overtopping. The principal purpose of this study is to assess the impact of the reservoir drawdown on the Chin Coulee landslide, which is believed to contribute to significant movements based on slope inclinometer records. The second purpose is to evaluate the landslide stability in the case where the water levels decrease for unusual periods and to propose an analytical approach for similar cases in the region.

Methods: To study the impact of drawdown on the landslide stability, the material properties of the Chin Coulee landslide were characterized using a combination of in situ and laboratory tests conducted in the area, such as Standard Penetration Tests (SPT), Index Tests, Triaxial Tests, and Direct Shear Tests. Additionally, we conducted a literature review to supplement our findings. Back analyses were then performed to calibrate the soil shear strength parameters required for the stability assessment. Finally, a numerical model was developed to simulate the landslide behavior under different reservoir water level scenarios and drawdown periods; and to estimate the overall landslide stability.

Results: The stability model results suggested that the landslide was unstable when considering the typical drawdown rate (Average 0.1m/day), which was consistent with the inclinometer records. The model also produced a non-circular slip surface, which was expected due to the weak shale coal underlying the Chin Coulee landslide. The back analysis enabled the identification of suitable parameters for tills and sedimentary materials, which are not extensively documented in the western Canadian prairies. This will help to fill gaps in the available data for these materials. As a result, an approach for analyzing these types of slopes that may be encountered in western Canada is proposed.

Conclusions: The findings of this study can help to have a better knowledge of landslides with these types of materials, developing guidelines and thresholds for managing reservoir water levels to mitigate landslide risk in the region. The proposed approach for analyzing slopes with typical western Canadian soils can be applied to other areas facing similar challenges, making this study relevant beyond the Chin Coulee area.

KINEMATIC EVOLUTION OF THE DEEP-SEATED, SLOW MOVING PISCIOTTA ROCK SLIDE (CAMPANIA, SOUTHERN ITALY)

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The Pisciotta rock slide is a deep-seated landslide involving about 6×106 m3 of heterogeneous and structurally complex flysch masses along the left valley of the Fiumicello torrent, nearby the Thyrrhenian coastline. The landslide threatens the SS447 road and a principal national railway which crosses the valley with a small bridge and continues throughout the landslide foot by a tunnel parallel to the landslide axis. In the last decades the landslide has caused huge and continuous deformations of the road, cracks in the tunnel lining, falling of rock blocks on the railway tracks, restriction of the Fiumicello torrent section at the landslide toe and consequent flooding of the railway tunnel. Besides the severe risk induced, the Pisciotta landslide is singular regarding the constant state of activity, at least since 1943, large ground deformations, causing the downslope movement of the SS447 for up to 70 m. In order to protect the precarious railway bridge at the landslide toe and strengthen the tunnel entrance, a series of works consisting in the construction of a prolongation of the tunnel across the valley, the culverting of the torrent and the earth-filling of the valley floor, up to 15 m, were carried out in the period 2018-2019. Since 2005, the middle-upper part of the landslide body, above the SS447, was monitored by topographic measurements of a series of optical targets, varying from 40 to 60. Specifically, four monitoring campaigns were executed covering almost continuously a period of about 16 years between August 2005 and September 2021. Therefore, in addition to the other peculiarities, the Pisciotta landslide is also remarkable for the availability of a long-lasting series of topographic monitoring.

By the integration of preceding analyses based on the first two monitoring campaigns with the last two ones, a more comprehensive reconstruction of the kinematic evolution of the landslide on a longer period was carried out in this research.

Among the principal results, the spatial distribution of displacements, velocities and deformation patterns showed a strong coherence with the landslide structures. The analysis of the temporal variability of the landslide kinematics revealed uncommon findings such that the landslide was always active in the whole monitoring period, with velocities ranging from the very low to low classes and maximum values observed unexpectedly in summer, during the dry period, with a delay of about six months from the rainy period. Interestingly, the global kinematics of the landslide showed the occurrence of four regimes with different mean velocity: 1) August 2005 - February 2012, with a value of 4.3 mm·day-1; 2) February 2012 - February 2014, with a value of 5.5 mm·day-1; 3) February 2014 - March 2019, with a value of 2.5 mm·day-1; 4) March 2019 - April 2021, with a value of 1.3 mm·day-1. The variability of the mean velocity was correlated to both long-term cumulative values of precipitation and, in the last period, to the effects of the stabilization works realized at the landslide toe.

DEVELOPMENT OF A ROCK SLOPE DAMAGE INTERACTION MATRIX USING A COMBINED CHARACTERIZATION-NUMERICAL MODELLING APPROACH

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Purpose: The stability of rock slopes is controlled by a variety of factors, including lithology, structural geology, and geomorphology, which may all contribute in defining the location, size, and kinematic mechanism of landslides. The occurrence of slope damage, however, also plays an important role in the long-term evolution of rock slopes. Slope damage, caused by earthquakes, geomorphic evolution, environmental changes, groundwater table variations, and time-dependent processes, results in a progressive weakening of the rock mass, allowing landslides to detach from slopes that were previously stable, in some cases changing the kinematic configuration of the slope.

Methods: Using a series of case studies and a combination of traditional and remote sensing methods and numerical modelling analyses, we analyze the role of a progressive accumulation of slope damage on the stability and evolution of rock slopes. We employ terrestrial/aerial laser scanning and photogrammetric datasets to map slope damage features at various scales and perform rock mass characterization. We use spectral datasets, including infrared thermography and hyperspectral scanning to investigate seepage and lithological changes at the slope and outcrop scales. Remote sensing and engineering geological field data are processed for use as input data for advanced numerical modelling analyses, including discontinuum (e.g., DEM), hybrid (e.g., FDEM), and lattice-scheme method with a focus on the factors that control and contribute to the development and accumulation of slope damage in rock slopes.

Results: Based on field and remote sensing characterization data, together with the results of numerical models, we observe that slope damage can constitute both the cause and effect of rock slope deformation. We demonstrate that the type and spatial distribution of slope damage is controlled by a combination of interacting factors. In turn, its role in controlling the slope kinematics and failure mechanism can vary significantly, based on the scale of the instability. To graphically summarize the results of this study, we developed a rock slope damage interaction matrix that highlight the role of structural configuration, rock mass quality, groundwater regime, and geomorphic evolution of the slope on the development of slope damage.

Conclusions: We observe that the analysis and characterization of rock slope damage can provide important insight in the mechanism through which instabilities develop. We note that, despite damage being a significant control on long-term slope stability, there is as yet no standardized approach for mapping slope damage. We emphasize that future research efforts should be directed towards the development of a framework for the systematic characterization and classification of slope damage, with the objective of improving the safety of infrastructure and the livelihood of communities affected by landslide risk.

PROBABILISTIC ESTIMATION OF DISPLACEMENT IN SEISMICALLY-INDUCED LANDSLIDES OF THE UPPER SELE RIVER VALLEY

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Purpose: On November 23, 1980, a strong earthquake (Magnitude 6.9 and duration over 60 s) hit the Campania and Basilicata regions of southern Italy, producing extensive damage and numerous fatalities (about 280.000 evacuate and 3000 fatalities). As a consequence of the event, many coseismic- and post-seismic slope instabilities occurred within an area of 7400 km2 and slope failure triggered as a consequence of the ground motion exhibited an accelerated displacement in the days following the event. These landslides concurred to damage settlements and interrupted many roads with significant implications on rescue delay and impossibility of reaching isolated mountains villages. The upper Sele river valley is among the areas that suffered major effect of both the earthquake and seismically induced landslides. Unstable slopes in the area are mostly formed by clayey and flyschoid formations emplaced as a consequence of a complex overlaps of tectonic-structural frames. A number of researches have shown how these kind of rocks are susceptible to slope instabilities and how landslides in the upper Sele river valley have been periodically active since their initiation/reactivation due to the November 23, 1980, earthquake. On this basis, and considering the ongoing kinematics of landslides in the area, as derived by Sentinel-1 based InSAR data, this study presents a probabilistic procedure to estimate landslide displacement under different seismicity scenarios.

Methods: A rigid block model that takes into account the initial pore pressure, the visco-plastic shear strengths evolution during sliding, and the effect of the vertical component of the ground motion on these strengths, as well as on the direction of the dynamic inertial loads induced has been developed and applied to selected landslides of the upper Sele Valley. The developed procedure is also able to probabilistically identify: i) seismic collapse of the slope induced by shear strengths decrease, promoting the perdured post-seismic mobility, ii) slope weakness highlighted by cracking phenomena formed during shaking, and iii) slopes areas where deformations are controlled by visco-plastic effects developed during fast shear rates in clayey soils. In this procedure, the spatial computation is performed in terms of regression laws formulated for the infinite slope model considering shear strength behavior derived by direct fast or impulsive shearing of clayey soils available in the literature. Statistical treatment of the input parameters is performed in a pre-processing stage and different input motion sets with different seismic energy (in terms of Housner Intensity), Arias intensity and spectral seismic parameters are used too.

Results: Results indicate how landslides potentially move in the near future as a consequence of seismic loading and that actively moving and suspended/dormant landslides can suffer acceleration/reactivation.

Conclusions: The proposed method is suitable for evaluating prospective change in kinematics of large and slow moving/suspended landslides. The obtained results can contribute to the knowledge of kinematics of landslides in the upper Sele river valley.

MULTIDISCIPLINARY SLOPE STABILITY ANALYSIS APPLIED TO CULTURAL AND NATURAL HERITAGE SITES IN CENTRAL ITALY

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Landslides in the vicinity of populated areas pose a constant threat socially, economically and culturally. The investigation and assessment of slope stability is essential for the safety and the sustainable development of cities as well as preservation of areas with cultural and social significance i.e. heritage sites. The Goal 11 of the United Nations “2030 Agenda for Sustainable Development” highlights the importance of ensuring and enhancing the resilience of communities and cities against disasters generated by extreme and natural events, such as landslides. In particular, Targets 11.4 and 11.5 call for strengthening the effort in the protection of natural and cultural heritage sites, and decrease the economic loss caused by disasters, respectively. Understanding potential hazards and proposing appropriate mitigation measures necessitates a comprehensive investigation of the problem from multiple perspectives, including structural, geotechnical, geomorphological, and trigger mechanisms through multi-disciplinary approaches. In this paper, we study the stability of a number of sites in Central Italy through use of remote sensing and numerical modelling. All selected sites have experienced slope failure in recent years and share a common lithological and geomorphological configuration, with a relatively massive and brittle rocky plateau overlying soft clayshales. All selected cases are also located within areas that host significant natural or cultural heritage sites. Using long-range laser scanning, UAV-photogrammetry and conventional structural mapping, we identified the major structures and mechanisms affecting the stability of these slopes. To better understand the failure mechanism responsible for the current morphology, we performed a back-analysis through numerical modelling based on the 3D model generated by laser scanning/UAV photogrammetry data combined with structural mapping. In addition, a repeat acquisition of long-range laser scan and UAV photogrammetry data over time allowed us to detect 3-dimensional slope displacement and assess the susceptible areas for future movement.

DIGITAL AERIAL PHOTOGRAMMETRY AND TIME-LAPSE ELECTRICAL RESISTIVITY TOMOGRAPHY (TL-ERT) IN LANDSLIDE MONITORING-AN EXAMPLE FROM POLAND

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Purpose: The main reason for the research was to propose an optimal and modern research methodology and modelling for an active landslides to understand reasons for activity.

Methods: Digital aerial photogrammetry is a remote sensing technique that allows you to reconstruct the topographic features of an area that has been previously photographed from the air. We can combine data from archival aerial photos with data obtained from airborne laser scanning. Thanks to this, we can trace surface changes in the landslide over many years. To illustrate the dynamics of the landslide located in the area of Dobrzyń (Figure1), archival aerial photos from 1974 and elevation data from air laser scanning from 2012 and 2019 were used.

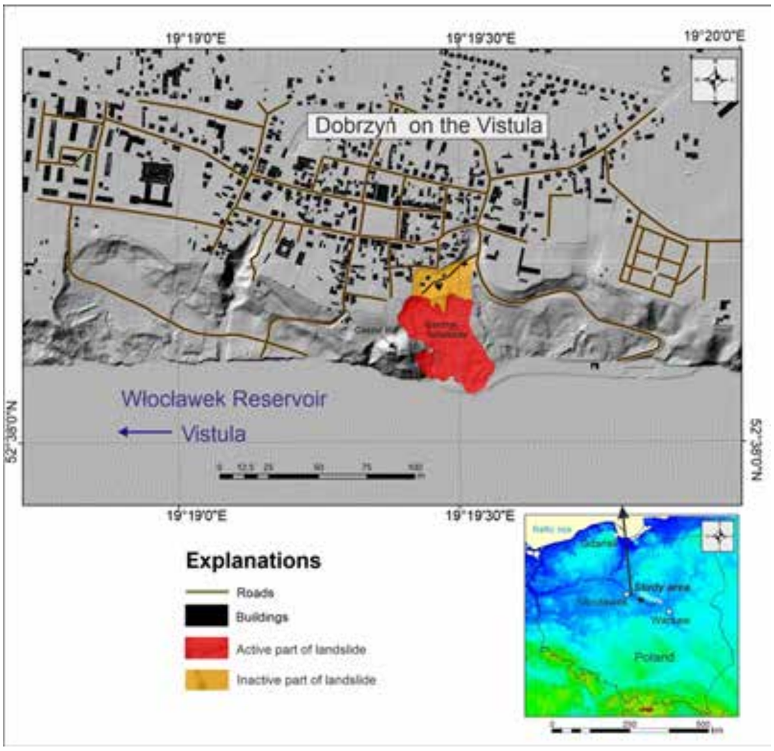

Fig. 1: Location of the study area.

Geophysical surveys ERT were carried out along a 120 m profile line running along the landslide. They were made in the spring of 2018, 2019 and 2020. The spacing of the electrodes was 2 m. The ERT method test involves recording changes in the electric field artificially created in the formation by a system of electrodes supplied with direct current. The measurements are usually made along straight lines at the ground surface. Time-lapse ERT provides images of the subsurface distribution of electrical resistivity over time, enabling the study of spatial and temporal changes in geological structures. The ERT measurement is sensitive to rock properties such as porosity, water saturation and salinity. The water saturation of the bedrock or colluvium is closely related to a higher landslide hazard.

Results: Differential photogrammetric models were the sources of new information about the dynamics of vertical displacement in the landslide and helped calculate the volume of displaced rock masses that occurred over 45 years. The differences between 1974-2012, and 1974-2019 models were visualized on the shaded relief map. In addition, morphological cross-sections were made by differential models, which presented changes in the landslide surface that occurred over time. The resistivity data allowed the interpretation of the faults and lithology of the bedrock geology, as well as the determination of the depth and geometry of the landslide slip surface. The generated TL-ERT differential models represented the percentage changes in saturation over time. Application the results of the geological interpretation of the electrical resistivity of the ERT profile and archival boreholes, a spatial model of the slip surface was generated.

Conclusions: The ERT surveys show that the landslide is mainly caused by rock lithology (clays) and glacitectonics deformations. The landslide was found to become significantly an active after 2010. This process was observed differential models and morphological sections. The analysis of differential geophysical and photogrammetric models, combined with data on the amount of rainfall, indicates that as a result of heavy rainfall and as a result of the rise in the groundwater level, the landslide is activated. Further investigation of the landslide will consist of combining aerial data with photogrammetric data from the unmanned aerial vehicle (UAV).

OPTIMIZING PREDICTION OF LANDSLIDES DEFORMATION THROUGH THE SYNTHESIS OF TEMPORAL RAINFALL DATA AND DEEP LEARNING STACKING ALGORITHM

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Purpose: Landslides are a common natural hazard that can have devastating impacts on communities and the environment. Accurately and reliably predicting the deformation of landslides is crucial for disaster management systems and risk reduction efforts. However, this remains a challenging task due to the spatial and temporal complexity involved in the process. This study focuses on the Randazzo landslides in the Alcantara River basin of northeastern Sicily, Italy. The goal of our research is to develop a Deep Learning Stacking Algorithm (DLSA) that can effectively predict landslides deformation by synthesizing temporal rainfall data and static predisposing geospatial factors and DLSA.

Methods: Current methods for predicting landslide deformation are limited in their ability to account for the Spatio-temporal interplay and interdependency between predisposing factors, rainfall time series, and cumulative deformation obtained by Permanent Scatterer Interferometry (PSI) and also is difficult to achieve with traditional statistical methods. To address these limitations, DLAs are able to learn complex patterns and relationships between features in large datasets, making them well-suited for analyzing landslide deformation data. We implemented a DLSA named Graph Convolutional Network-Long and Short-Term Memory (GCN-LSTM) to predict cumulative landslide deformation. To achieve this, we used a stacking method to concatenate the effects of predisposing factors and rainfall time series data on predicting cumulative landslide deformation on a specific time step in the test set. We implemented two DLAs, one for predisposing features and one for rainfall time series, both of which were labeled according to cumulative deformation obtained by PSI. We used a GCN regression to capture the effect of static features and a GCN-LSTM multivariate time series to consider Spatio-temporal dependency between features. The outputs of both models were combined using the stacking strategy, with hyperparameters tuned, particularly the correlation distance, which measures spatial interdependence between data points. The correlation distance was then fed into a multivariate time series GCN-LSTM to capture cumulative predictions for the entire test set.

Results: The proposed algorithm was validated using several DLAs, including Simple RNN, GRU, and LSTM. Our proposed multivariate time series GCN-LSTM algorithm outperformed non-spatial models in detecting the behavior of 2958 data points from 2011 to 2014 from 69 cumulative landslide deformations and rainfall simultaneously. The algorithm is able to describe the spatial and temporal behavior of data points while predicting the future amount of landslide deformation, outperforming traditional DLAs.

Table: Evaluation metrics for the second modeling approach

Model		Evaluation Index			
		(MSE)	(MAE)	(RMSE)	R-squared
First Step	GCN	0.08	0.19	0.28	0.83
RNNs with temporal dependency (Second Step)	Simple RNN	1.41	0.84	1.18	0.72
	GRU	1.18	0.91	0.96	0.85
	LSTM	1.34	0.89	1.02	0.81
Proposed stacking modeling approach (Spatio-temporal dependency)	GCN-LSTM	0.13	0.22	0.29	0.91

Conclusions: In conclusion, our study highlights the importance of considering Spatio-temporal interdependency between data points in predicting landslide deformation. The proposed DLSA effectively predicts future landslide deformation, demonstrating DLAs' potential in landslide studies. It can reduce the negative impacts of landslides on communities and the environment by providing a reliable algorithm to predict future landslide deformation.

THREE DIMENSIONAL BACK ANALYSIS OF LANDSLIDE INVENTORIES TO EVALUATE TRENDS IN STRENGTH AT LARGE SPATIAL SCALES

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Oregon State University

Purpose: Landslide inventories are critical datasets for evaluating landslide susceptibility, hazard and risk analyses, as well as insight towards geologic and topographic controls on various landslide mechanisms. However, these datasets have significant potential as a means of inferring mechanical properties and associated uncertainties that potentially control mechanism or reflect weathering and geologic controls on instability. Through a fusion of high-resolution lidar and landslide inventories, we perform three-dimensional back-analyses on thousands of landslide deposits, both in their current state and within their estimated, reconstructed source area. Through these analyses, we seek to understand associations of mechanical properties with landslide size, mechanism, geologic unit, and both climatic and tectonic settings.

Methods: The proposed approach uses the State of Oregon landslide database (SLIDO, Burns and Madin 2009) along with 0.91 m lidar DEMs (Oregon Lidar Consortium) to isolate topographic conditions for each landslide. Thereafter, using a thin plate spline technique, we infer rupture surface geometry based on projections of headscarps (Bunn et al. 2020a, Alberti et al. 2022) and reconstructed surface topography using curvature-preserving inpainting techniques. We then perform three-dimensional slope stability analyses to infer friction angles from at-rest landslide deposits and cohesion from reconstructed landslide geometries (Bunn et al. 2020b, Alberti et al. 2022). Thereafter, a systematic comparison between landslide strength and various topographic, geologic and morphometric variables is considered.

Results: Landslide size tends to be interrelated with back-analyzed strength as smaller deposits tend to have higher friction angles and lower cohesion values. Large landslides tend to have lower friction angles and higher proportional cohesion. We observe that there are distinct differences between landslide strength values based on mechanism and geologic unit, where bedrock landslides tend to have more cohesion than soil landslides, and some geologic units are much weaker than others. We also demonstrate that these trends in strength may serve as one type of proxy for subsurface weathering. These back-analyzed strength values can be used to parametrize the heterogeneity in strength values for physically-based landslide susceptibility and hazard models.

Conclusions: We demonstrate new applications for landslide inventories when fused with three-dimensional slope stability. These analyses reflect that surface and inferred subsurface characteristics of inventoried landslides may serve as an inversion of mechanical properties when used with advanced slope stability models. These data may serve to constrain mechanical controls on landslide mechanism and size, among other inferences.

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SESSION 1.1

INTERNATIONAL PROGRAMME ON LANDSLIDES AND GLOBAL AND INTERNATIONAL ACTIVITIES FOR KLC2020 (part I)

MONITORING MULTI-STAKEHOLDERS' CONTRIBUTIONS FOR BUILDING RESILIENCE AGAINST LANDSLIDES THROUGH THE SENDAI FRAMEWORK VOLUNTARY COMMITMENTS ONLINE PLATFORM

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United Nations Office for Disaster Risk Reduction Kobe Office

Purpose: Disasters caused by landslides have continued to occur in recent years resulting in loss of lives and livelihoods around the world. To prevent such disasters from occurring and to reduce risks to landslides, it is crucial to share good practices of stakeholders around the world and promote all-of-society engagement. The Sendai Framework Voluntary Commitments (SFVC) online platform continues to take stock and monitor non-state actors' contribution to the Sendai Framework for Disaster Risk Reduction. Not only does the platform keep track of their contribution to the Sendai Framework global targets, but it also details the hazards each commitment is aiming to address, including landslides.

Methods: As of February 2023, a total of 113 voluntary commitments have been published on the SFVC online platform. This article provides a quantitative and qualitative analysis of these voluntary commitments looking into their deliverables, budgets, participating organizations, Sendai Framework targets and SDGs covered, among other variables. The quantitative analysis involves descriptive statistics that provides particular insight on commitments that are addressing landslides in their disaster risk reduction activities. Additionally, the article presents case studies to showcase noteworthy commitments implemented by stakeholders that are taking great strides in reducing risks from landslides.

Results: As of February 2023, 66 per cent of the voluntary commitments submitted by stakeholders is implementing activities to build resilience against landslides. Initial findings indicate that landslides as a hazard is the third most tackled hazard among the 17 hazards documented on the SFVC online platform. These 75 commitments have committed a total of 386 deliverables related to disaster risk reduction and involve a total of 543 organizations. The commitments vary in scope – 32 per cent have a global scope, 25 per cent have a regional scope and 43 per cent have a national scope. The themes and issues most commonly covered by these commitments are disaster risk management, capacity development, and risk identification and assessment, which are consistent with the Sendai Framework priority covered by most VCs, which is Priority 1 Understanding Risk.

Conclusions: Although a majority of the voluntary commitments cover landslides as a hazard in their disaster risk reduction efforts, it would be beneficial to encourage more action and improve current activities specific to landslide risk reduction especially for countries more vulnerable to landslides. The Sendai Framework Voluntary Commitments online platform endeavors to mobilize more stakeholders to address landslides as hazards striving for a world where landslide risks no longer threaten communities.

REVIEW AND WAY FORWARD OF THE OPEN ACCESS BOOK SERIES “PROGRESS IN LANDSLIDE RESEARCH AND TECHNOLOGY” FOR THE KYOTO LANDSLIDE COMMITMENT 2020

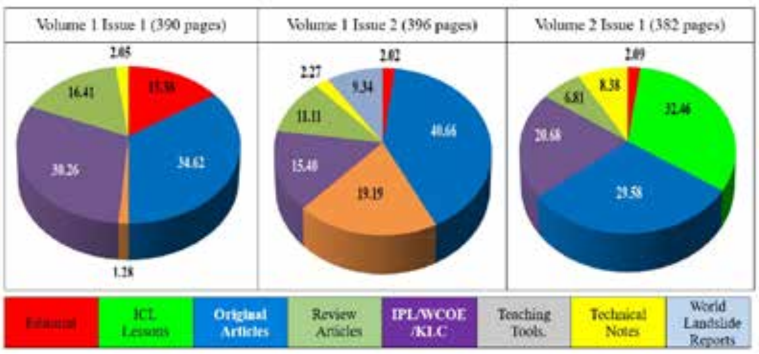
Sassa Kyoji
International Consortium on Landslides

Purpose: Progress in Landslide Research and Technology is a new Open Access book serie of the International Consortium on Landslides (ICL). This series offers a shared platform for publishing recent progress in landslide research and technology, especially with practical applications and the benefit for the society, thereby contributing to the Kyoto Landslide Commitment 2020 launched on 5 November 2020. This presentation aims to review the state of the open access book series from the initial issues that have already been published, namely Vol.1, Issue 1 and Issue 2, as well as all papers that will be published in the second issue Vol.2 Issue 1. Papers for Volume 2, issue 2 are expected to be submitted and accepted before the Sixth World Landslide Forum (WLF6). Based on the analysis of three to four issues, the further development plan of the series, especially for 2024 and beyond is examined. This plan will be shared with participants in theme 1 session 1 during the WLF6.

Methods: This presentation firstly describes the financial background of the book series, including the book processing charge (BPC) and the KLC2020 official promoters which promote the book series including financial contribution. Secondly, the article editing system and the decision-making process of the issue editors who are printed on the cover of each issue, are discussed. This book series publication is one of the core activities of the International Programme on Landslides (IPL), a science programme of the International Consortium on Landslides (ICL) for Landslide Disaster Risk Reduction. The category of IPL/WCOE/KLC activities is created for the promotion of publication of IPL projects and WCOE activities.

Examination of categories: This book series aims to facilitate the practical application of landslide science. The book emphasizes the promotion of technical transfer and capacity building through information dissemination. The advantages of open access publication are the most effective. Categories of the Teaching tools with video tutorials, the ICL landslide lessons, and the World Landslide Reports are topical characters of this book series.

Results: Share (%) of six categories in page number examined for the first three issues is presented in the following table.



Conclusions: The access statistics for the first two issues of the book series are impressive with Volume 1, Issue 1 and Volume, Issue 2 published on 10 January 2023 receiving 34,000 and 31,000 accesses respectively within the first two months (on 8 March 2023). This free and seamless downloading of the whole book series is available to every one.

Progress in Landslide Research and Technology, Volume 1 Issue 2, 2022 SpringerLink (https://link.springer.com/book/10.1007/978-3-031-16898-7)

We have taken the following measures to promote contribution, and taken a new initiative to promote this open access book series. Thanks to the KLC2020 official promoters, we keep the book processing charge (BPC) low: 50 USD/page less than 20 pages, 40 USD/page more than 20 pages for regular. BPC for ICL full members and KLC2020 official promoters are zero until 10 pages/year.

The contribution of articles is the most important. Initially, the editorial team for Volume 1 Issue 1 comprised five members, but editors who have contributed more than two articles in recent issues are now invited to serve as cover editors for each issue. Book cover editors Volume 1 Issue 2 were 9, and this increased to 11 due to the increase of contribution. The front cover photo was selected from the published articles through discussions among the editors. This book is a result of joint works by involved editors. To further promote good articles, we have started the two new Awards: A: ICL Book Article Award, with 1-3 awards granted every year, provides free BPC for 20 pages, B: IPL-KLC Award for Success, with 1-3 awards granted every three years at each WLF, includes a cash prize of 3,000 USD.

INTRODUCTION AND PROMOTION OF WLF7 IN TAIWAN 2026

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Purpose: National Central University (NCU) and the Chinese Taipei Geotechnical Society (CTGS) are promoting the preliminary introduction of WLF 7 in Taiwan. The proposed event, scheduled for June 22nd-28th, 2026, will include a 2-day field visit and will be held at NCU hall, which offers various meeting rooms and exhibition spaces.

Methods/Result: The National Central University (NCU) and the Chinese Taipei Geotechnical Society (CTGS) have given their support to the proposal for WLF 7 in 2026. As a full member of the International Consortium on Landslides (ICL), NCU is committed to addressing the critical issues related to landslides, such as mapping, characterization, testing, monitoring, modeling, and risk assessment. NCU's centrifuge laboratory, which is the only one of its kind in Taiwan, allows for excellent landslide modeling. On the other hand, CTGS is a member of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) and is actively involved in various international activities of the organization. The association aims to host international conferences that will increase Taiwan's international visibility and promote opportunities for international cooperation in the development of various geotechnical technologies.

- The main WLF7 information:
- Host: National Central University & Chinese Taipei Geotechnical Society
- Date: 2026.6.22~26 for Conference. 2026/6/27-28 Field Trip
- City: TaoYuan (close to Airport and Taipei)
- Venue: NCU main Hall with 10 meeting rooms and 50 exhibition booths
- Estimated Number of Participants: 600~800 persons
- Registration Fee
- Early Bird 500 USD (ICL Board & Deputy Member free support / ICL Associate 2 max. free)
- Other 600 USD
- Onsite 800 USD
- Field Trip (2 days) 300 USD

Conclusions: Taiwan (Taipei/Taoyuan) has easily affordable traveling and living expenses. Taiwan has advantages of Visa-exempt entry for more than 45 countries, a short flight away to most major cities in Asia, easy access to mobile network and free Wi-Fi, and 24-hour operated amenities satisfy all your needs. Most important, Taiwan is one of the top 10 safest countries in the world.


Figure: 1 NCU hall.


Figure 2. Meeting room and exhibition locations.

RESEARCH AND DEVELOPMENT OF CORE TECHNOLOGY AND ITS APPLICATION FOR EARLY WARNING IN LANDSLIDES - INTRODUCTION OF THE SINO-JAPAN COLLABORATION PROJECT

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Purpose: Slope monitoring and early warning systems (EWS) are promising approaches to mitigating landslide-induced disasters. Many large-scale sediment disasters destroy infrastructure and loss of human life. The mitigation of vulnerability to slope and landslide hazards will benefit significantly from early warning alerts. Through the Sino-Japan collaboration project of the Japan International Cooperation Agency (JICA) and the Ministry of Science and Technology of China (MOST), a core technology of 'A risk evaluation method of unstable slopes using multipoint tilting sensors' is applied in Yangtze river basin. Establish an early warning threshold for landslide disasters due to rainfall, develop an early warning system, and demonstrate an experiment in China.

Methods:

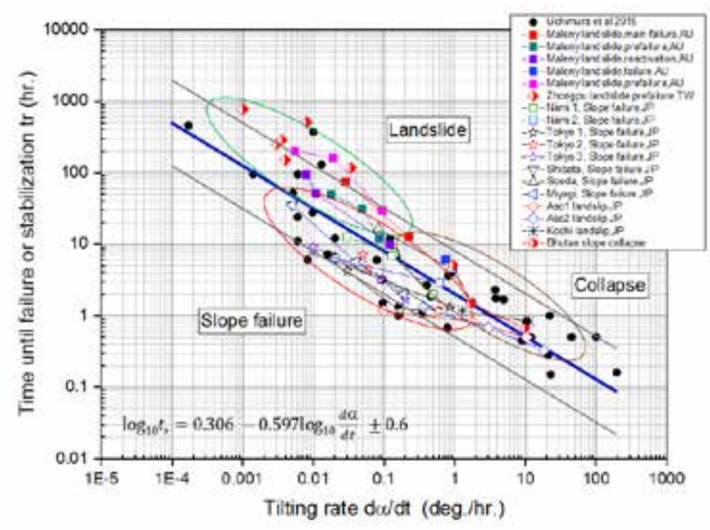
The authors have been developing monitoring technology that uses a Micro Electro Mechanical Systems (MEMS) tilt sensor array that detects the precursory movement of vulnerable slopes and informs the issuance of emergency caution and warning alerts. In this regard, the determination of alarm thresholds is very important. The authors prefer tilt sensors and have proposed a novel threshold for the tilt angle, which was validated in this study. Additionally, multi-point monitoring has recently emerged and allows for many sensors to be deployed at vulnerable slopes without disregarding the slope's precursory local behavior. With this new technology, the detailed spatial and temporal variation of the behavior of vulnerable slopes can be determined as the displacement proceeds toward failure.

Results: Forecast of the remaining time until landslide and slope failure as shown in the following figure which has considered landslides, slope failure, collapse, and field experiments since 2004. While the overall trend of the obtained data in the figure is similar to the Saito model, it is further proposed that three different failure times may affect the plotted relationship by our recent research

$$log_{10}t_r = 0.306 - 0.597log_{10}\frac{d\alpha}{dt} \pm 0.6$$

where tr denotes the time remaining until failure (hours) and dα/dt denote the rate of the tilting angle (degree/hour).

Conclusions: This paper introduces the most recent development of the authors' EWS based on data obtained from several sites and their interpretation. As for the actual plans, the authors are currently undertaking the National key R&D project of Sino-Japan "Development and demonstration of monitoring and warning technology for the rainstorm induced mountain torrent disaster chain", which takes the rainstorm-flood-landslide-debris flow disaster chain as the research object and is carrying out through international cooperation and joint research. The results such as deeply exploring the occurrence and evolution mechanism and developing the key technologies for precise monitoring and dynamic warning of the rainstorm-induced mountain flood disaster chain are expected to be obtained. The project aims to provide scientific and technological support for the mountain flood disaster chain prevention and control, and effectively improve the theoretical and technological level of disaster prevention and reduction research between China and Japan.



LANDSLIDE QUANTITATIVE RISK ASSESMENT FOR DEVELOPING COUNTRIES IN A DENSELY POPULATED URBAN CONTEXT: THE CASE OF THE HIGH CITY OF ANTANANARIVO (MADAGASCAR)

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Developing countries are more and more facing the consequences of climate change with impacts strongly affecting dense urban settlements, which threaten their often fragile and precarious setting. In this framework, we operated a landslide quantitative risk assessment in the High City of Antananarivo, Madagascar's capital. The city is often affected by cyclones responsible for intense precipitations resulting in correlated landslide and flooding phenomena. Built on the hilltop of the Analamanga Hill, a granite ridge overlooking the Ikopa River valley, the High city presents heterogeneous construction typologies: neo-gothic cathedrals and neo-baroque palaces (such as the royal palace "the Rova"), together with private historically buildings, often presenting wood or bricks structures. The hillsides are draped with an alternation of quarters formed by concrete two or multi-story buildings (generally occupying the northern hill areas) and poor housings (especially in the southern sectors). The Analamanga Hill geomorphological setting is characterized by asymmetric slopes with a steeper western hillside, formed on the top by a subvertical jointed granite rock cliff (where rockfalls mainly occur), overlying a colluvial footslope formed by residual lateritic soils, oftentimes affected by deep U-shaped gullies (where debris flow may potentially channel). A general minor slope angle (mean values ≈30°) is found on the eastern hillside where lateritic soils are locally affected by channelled creek and sheet-overland flow erosion. The hill's southern sector is characterized by steep slopes where diffuse and intense quarrying activity left excavation niches that now evolved in more rockfall source areas. The northern sector presents strong urbanization that has obliterated the geomorphological structures and gently links the slope with the river plain. In the winter of 2015 heavy rainfall connected to cyclones triggered several diffused soil slips, while between the winters of 2018 and 2019 several rockfalls occurred from the western rock cliff, claiming several lives. As the Analamanga Hill and its buffer area are a UNESCO tentative site, a landslide quantitative risk assessment was carried out in the framework of the Dossier for the enrolment of the High City in the UNESCO World Heritage List, in collaboration with RC-Heritage consultants and Paris Region Expertise – Madagascar. The research first focussed on the determination of landslide hazard, considering the various processes affecting the area (rockfall, soil slip, gully channelled debris flows), followed by the assessment of vulnerability on the building characteristics and exposure, considering the occurrence of a phenomenon with maximum intensity. These activities were carried out in several field campaigns, using remote sensing techniques (satellite and drone-based), GIS techniques, as well as machine learning-runout models. Despite the method developed, the exposure assessment had an inherent complexity arising from the city complex urban and social structure, as well as the presence of cultural assets. The output of this methodology allowed us to quantitively assess the areas more exposed to landslide risk, also providing a valuable tool for urban planners and policy makers to reduce the risks connected to the phenomena, improve housing safety for all the population and to preserve the cultural heritage of the city.

INTERNATIONAL PANEL OF EXPERTS ON LANDSLIDE RISK FOR CULTURAL HERITAGE SITES (NICHE)

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Cultural Heritage sites that are exposed to adverse environmental effects are many, as we witness a lot of deterioration and loss of value of cultural heritage sites due to landslides, block movements, geological and hydrological deterioration, etc.

While several cultural heritage sites are built of natural materials (Sphinx statute in Egypt, Buddha statutes in Afghanistan, etc.), are being carved or built in rocks (Petra in Jordan, Rock-Hewn Churches of Ivanovo in Bulgaria, etc.), or being built on natural cliffs and slopes (Machu Picchu in Peru, Eldeir Elbahari in Egypt, etc.), those cultural heritage sites are heavily affected by their natural environment and the deterioration of constitutive rocks.

Governments and municipalities concerned with maintenance, safeguarding and conservation of those cultural heritage sites spend huge amount of money and resources to keep those sites in a good condition, as they constitute part of the country's wealth and heritage (in addition to Tourism).

The main aim of this project is to bring the vast expertise and knowledge of the ICL members voluntarily to the service of the government / communities in charge of cultural heritage sites, and to give advice on tools and techniques of restoration and safeguarding against landslide and block movements risks.

We believe that by building the capacity of local government and municipalities, in addition to guiding local populations in countries that are not wealthy enough to pay for high fees consultation, would lead to raising awareness of problems facing cultural heritage sites and raising funds necessary for the safeguarding and conservation of those sites.

The three authors that are proposing this project are considered as the core team of expertise. A call for expertise will be sent to all ICL members, to express their willingness to join the larger pool of expertise and enrich its membership.

While the sustainability of the funding for the activities of the project is a potential problem, but the members of the core team, and eventually the larger pool of expert will work on applying for other projects and funding, under the label of IPL.

The final objective of the project is to create a pool of expertise and a portfolio of voluntary interventions from ICL members that are able to help and give consultations for governments and municipalities / Capacity Building workshops and trainings about how to safeguard Cultural heritage Sites against adverse natural effects of landslides and other Geo Environmental hazards.

ACTIONS AND CONTRIBUTIONS OF INTEGRATED RESEARCH ON DISASTER RISK TO KYOTO LANDSLIDE COMMITMENT 2020

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Purpose: Integrated Research on Disaster Risk (IRDR) officially joined the Sendai Landslide Partnerships 2015-2025 at the 4th World Landslide Forum in 2017 and pledged to contribute to the risk reduction on landslide through its research networks. The Kyoto Landslide Commitment (KLC) 2020 further underscored the changing risk landscape related landslides and outlined key actions in research and capacity building. Through its capacities as a DRR knowledge-action community, IRDR contributed to KLC2020 from the aspects of risk assessment, improving science-policy interface to the understanding of risk of landslides, and from its actions toward early warning system development and fostering initiatives to enhance DRR capacity building in countries.

Methods: IRDR Scientific Committee (SC) provides the overall guidance on research priorities of IRDR, including its commitment to international DRR cooperation for example the Sendai Landslide Partnerships. After 2017, IRDR SC promoted in particular the innovation work on risk reduction of landslide. Following its integrated and interdisciplinary approach, IRDR international centers of excellence (ICoEs) and other entities took initiatives, in forms of IRDR Working Groups and Flagship Projects, and IRDR Work Streams and Pilot Studies commenced in IRDR Phase II. Through IRDR ICoEs and IRDR young professionals, IRDR acts as a multi-disciplinary knowledge producer contributing to DRR institutional capacity development, and performing as science-policy-practice interface to promote solution-oriented research and service. IRDR Working Paper Series, policy briefs, special reports, and its convening service in organizing science and policy forums are accessible for the promotion of landslide risk research and successful DRR application examples.

Results: Some IRDR contributions can be highlighted, including: a concept of new impacted based multi-hazard early warning system by the Working Group on Risk Interpretation and Action; a Landslide Dataset by IRDR National Committee of New Zealand to develop new earthquake-induced landslide forecasting models; the multi-scale risk assessment of landslide and the impacted infrastructures along the silk and road region by IRDR Flagship Project SiDRR. IRDR also promoted the studies on understanding landslide risk such as community vulnerability to landslide in Indian Himalayan Region and infrastructure risk of landslide in the permafrost areas in China. IRDR called for international cooperation to reduce the risk of landslide at UNESCO International Designate Sites at the 4th Huangshan Dialogue and the 5th World Landslide Forum. IRDR supports the IRDR young scientists on their research and risk reduction practices on landslide. In addition, IRDR IPO actively participated in ICL/IPL related conferences and meetings after 2017.

Conclusions: The new Global Risk Science Research Framework, published in 2021 by ISC, UNDRR and IRDR, provides new opportunities to further enhance its contribution toward the Sendai Landslide Partnerships and KLC2020. IRDR will continue its role in advancing DRR related research, foresight studies, publication, advocacy and science-policy-society discourse. A Work Stream to further contribute toward KLC2020 is highly desired to be established to address the risk nexus of geology, hydrology, technology and society on landslide.

STUDY ON TECHNOLOGY FOR FORECASTING AND EARLY WARNING LARGE-SCALE LANDSLIDES IN VIETNAM'S HILLY AREAS

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Purpose: In Vietnam, abnormal weather conditions in recent years have led to many heavy rainfalls, resulting in several large-scale landslides that caused not only property damage but also claimed the lives of many people. The mountainous regions experience frequent landslides and floods, with an average of 15-16 incidents per year. Due to the dynamic characteristics and potential for causing large-scale disasters, the technologies for forecasting and warning of large-scale landslides have received great attention from relevant agencies and localities. Early warning systems for large landslide disasters have been established with the aim of protecting various important structures.

Methods: The combination of remote sensing analysis and geographic information systems (GIS) is considered one of the most effective methods. To obtain detailed images of the characteristics and size of the landslide, especially in difficult-to-access locations, unmanned aerial vehicles (UAVs) are used. Detailed flight path programming helps to collect a large number of images, and create a 3D model of the large-scale landslide using Agisoft software and basic analysis of the digital surface model. The monitoring systems including the use of sensors to measure rainfall, water pressure in pore spaces, and horizontal displacement are employed. The wide measurement ranges of sensors allow them to be placed in areas with large displacement or at depths with high pressure. An important part of the early warning system for large landslides is monitoring the movement of the landslide every hour, every minute. Data processing tools commonly used are statistical methods to evaluate correlation, combined with data analysis using machine learning methods to build forecasting and warning models. In addition, the method of determining the affected area of the landslide by numerical modeling with LS-Rapid software is also employed.

Results: Several systems for early warning of large-scale landslides in Vietnam have been established to protect various important infrastructure projects. Currently, the VNU University of Science, Hanoi is maintaining 4 large-scale landslide monitoring stations. Forecasts of landslide risk have been regularly published by the research team on the website www.truotlo.com and on social media platforms such as Facebook and Zalo.

a **b** **c** **d**

Fig. Large-scale landslide monitoring stations at the sites (a) Nam Dan, Xin Man, Ha Giang, (b) Ban Diu, Xin Man, Ha Giang, (c) Takpor, Nam Tra My, Quang Nam, and (d) Kham Duc, Phuoc Son, Quang Nam.

Conclusions: The effectiveness of early warning systems for large landslides has gradually been demonstrated in practical life. Notably, in places where early warning systems for large landslides have been installed, local residents have become aware of their importance and have participated in protecting, maintaining, and providing relevant information. In addition, data collected from monitoring systems help researchers gain a better understanding of the dynamic process of large-scale landslide.

SESSION 2.1

CASE STUDIES AND STATE OF THE ART ON LANDSLIDE MONITORING (part I)

REMOTE SENSING TECHNIQUES TO ENHANCE EARLY-WARNING GROUND MONITORING NETWORKS MANAGEMENT

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Purpose: Landslides are widespread on the Italian Alps, causing every year a significant number of fatalities and huge economic losses. In this region, slope instabilities with different dimensions, kinematics, and evolution mechanisms, including different types of movement, going from small scale rockfalls to deep seated gravitational deformations affecting entire slopes, have been recognized and are currently monitored by the Geological Monitoring Centre (CMG) of ARPA Lombardia. The CMG is dealing with 45 landslides monitoring networks. Among these, 34 are set-up with real-time data transmission and 29 have early-warning purposes. In this framework, we explored the capabilities of InSAR techniques to:

- Characterize and mapping the landslide areas, to improve the ground monitoring network design.
- Integrate remote sensing and ground monitoring data, to reach a deeper knowledge of the landslide phenomena movement trend and kinematic behaviour, to chase a comprehensive understanding of such instabilities and of their evolution in alpine areas characterized by climate change and an increasing anthropogenic pressure.

Methods: The SqueeSAR® analysis has been carried out on the 45 instabilities by processing high-resolution images, acquired by the COSMO-SkyMed (CSK) and COSMO-SkyMed Second Generation (CSG) satellites, in ascending and descending geometry, covering the period January 2010 – November 2022. Ascending and descending geometries results have been combined to get vertical and east-west deformation components. Time series were analysed using a specific algorithm to recognize non-linear trends in the displacement patterns. CSK SqueeSAR® results were compared with Sentinel (SNT) data processed over similar areas in the same period and integrated with ground monitoring findings.

Results: The interferometric analyses led to a good coverage with more than 3,000 MP/Km^2 in each geometry, despite well-known challenges for SAR-Interferometry in alpine environments, as the significant difference in altitude and slope orientation within small areas, snow cover and vegetation. Radar interferometry, thanks to both spatial and temporal coverage, provided essential information regarding the perimeter of the various phenomena, their state of activity, the presence of areas with different evolutionary behaviours and the general evolution of the slope instabilities over time. During the climate anomaly registered in 2022, both ground monitoring network and remote sensing data, highlighted a reduction of the slope displacements. The remote sensing data acquired in the last two years led to the identification of areas where ground-based monitoring networks were to be implemented. During 2022, GPS benchmarks with dual-frequency antenna were installed in the selected locations.

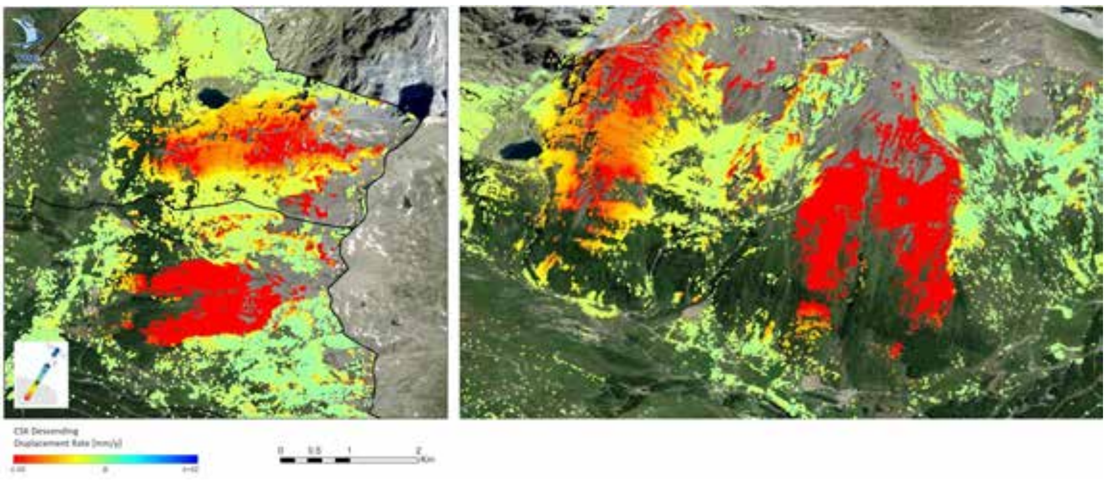

Fig: 1. 2D (left) and 3D (right) visualization of the displacement rate on the Mater and Emet instabilities (Italian Alps) - descending geometry.

Conclusions: Satellite interferometry offers several advantages on landslide detection and monitoring. The use of a high-resolution satellite provided a higher density of measurement points (MP) than a medium-resolution satellite, such as Sentinel. This resulted in detailed characterization and mapping of the landslide areas and a discrimination between the more or less active sectors within them (e.g., nested landslides) as well as increased effectiveness when re-designing ground-based monitoring networks, which would have been less effective with the use of a medium-resolution satellite. The temporal frequency of the satellite acquisitions was recognized to have a key role in identifying movement acceleration and avoid underestimations of trend changes.

ENHANCING LANDSLIDE RISK MITIGATION THROUGH SATELLITE INSAR DATA: INSIGHTS FROM JAPAN'S EXPERIENCE

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Remote sensing is a powerful tool for mitigating risk associated with landslides. In Japan, the National Research Institute for Earth Science and Disaster Resilience (NIED) has recently published nationwide landslide catalog based on photo interpretation. However, active landslides - particularly those characterized by slow displacement rates – are difficult to identify without field research. In addition to in situ instruments and photo interpretation, satellite radar data can provide useful information for monitoring unstable slopes: in fact, by analyzing the time series of displacement data and velocity values of a sliding area, it is possible – at least in some cases - to estimate the time of failure, through the Fukuzono method. The vertical and east-west displacement components provided by InSAR analysis can be calibrated and integrated with in situ measurements to provide invaluable information, provided that the level of coherence of the radar signal is high enough in multi-temporal observations and the spatial density of measurement points can allow the modelling of the local dynamic.

Commercially available satellite SAR images are acquired at three frequency bands: X-band (3-cm wavelength), C-band (6-cm) and L-band (24-cm). C-band Sentinel-1 ESA sensors have been acquiring SAR images over Japan every 12 days since 2014, but the spatial density of InSAR measurement points is quite low over vegetated areas, making it difficult the identification of some landslide footprints. Yet, in 2019, TRE ALTAMIRA and OYO carried out the first nationwide landslide mapping effort in Japan using Sentinel-1 imagery, allowing the identification of hundreds of landslides, areas affected by subsidence, and surface deformation phenomena induced by volcanic and/or seismic activity.

High-resolution X-band satellites, such as COSMO-SkyMed and TerraSAR-X, are creating large InSAR data stacks over Japan, but most of them cover urban areas only and their performance in vegetated areas is quite poor, at least as InSAR applications are concerned. In fact, Japan's heavily forested land area, which covers almost two-thirds of the country, necessitates the use of L-band SAR satellites, which can better penetrate vegetation and provide a relatively high level of coherence over most of the country. However, L-band satellites have a lower sensitivity to small terrain changes and displacements than satellite platforms equipped with C-band or X-band sensors. In the past, the acquisition interval of L-band satellite sensors used to be more than 40 days (44 days for J-ERS and 46 days for ALOS-1 PALSAR), making it difficult to use them to support early warning systems for natural disasters, but more recent missions feature much more frequent acquisitions (14 days for ALOS-2 and 12 days for the future NISAR mission).

ALOS-2 data has recently been used to identify landslides near the Odo Dam, as well as sliding areas along important highways. In addition, InSAR data has complemented the NIED database and allowed for the identification of new phenomena. This paper reports interesting results obtained at different frequency bands and over different types of terrain. Furthermore, it highlights how the development of more sophisticated processing algorithms has significantly increased the amount of information that can be extracted from satellite SAR datasets. Recent results have also confirmed the complementarity of satellite data with in situ measurements.

Japan's increasing vulnerability to natural disasters caused by global warming highlights the need for nationwide satellite monitoring to prevent and mitigate potential losses. Nationwide satellite monitoring will play a crucial role in enhancing disaster prevention and improving national resilience

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A SYNTHETIC APERTURE RADAR INTERFEROMTERY PERSPECTIVE ON INSTABILITY OF JOSHIMATH, INDIA

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Purpose: Joshimath, a holy town of Chamoli (Uttarakhand, India), witnessed a rapid subsidence event since last week of December-2022 to first week of January-2023 claiming cracks in more than 700 homes and evacuation of more than 2000 peoples. The cracks developing in houses are reported since more than a year in 2021 which became worse in the beginning of the year 2023. In most of the alleged causes of the event, the vulnerable foundation of the Joshimath as it is located on an ancient landslide and a currently running Tapovan_ Vishnugad hydroelectric project are considered most important factors behind the instability. This study aims to provide an InSAR (Synthetic Aperture Radar Interferomtry), one of the established methods of landslide monitoring and identification, perspective on the instability of Joshimath.

Methods: We processed 47 descending and 60 ascending Sentinel-1A scenes of period Jan-2021 to Jun-2022 and Jan-2021 to Dec-2022, respectively using StaMPS (Stanford Method for Persistent Scatterers (PS)) package and identified many PS pixels with unstable displacement trend.

Results: We classified the whole region into stable and unstable pixels and investigated for unstable zones with respect to hyderoelectic project and locations of damaged houses. Additionally, we also attempt to inspect contribution of few more potential landslide conditioning factors such as the geology, climate and haphazard construction of roads and infrastructure development in the instability of Joshimath.

Conclusions: InSAR derived unstable and stable zones rae successfully identified along with contributioin of othe landslide conditioning factors. As per the capability of InSAR, this study is primarily a small contribution towards development of InSAR based early warning system.

EXPLORING POLARIMETRIC SYNTHETIC APERTURE RADAR (POLSAR) POTENTIALITY FOR LANDSLIDE DETECTION. CASE STUDY: LARGE-SCALE LANDSLIDE IN THE PAN-AMERICAN HIGHWAY CORRIDOR IN THE ANDES MOUNTAIN REGION IN COLOMBIA

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Background: Tropical mountain regions face adverse and worsening geohazards caused by climate related conditions, affecting large geographic areas worldwide. Landslides not only cause affectation to the people life, but they can affect the infrastructure challenging the ability of emergency authorities to assess the extent of the affected area. In Colombia, road transportation sector is severely affected, mainly during the rainy season, resulting in increasing road closures and costly damages. A prompt landslide detection and mapping of the affected areas is crucial for a fast response and intervention. Satellite Synthetic Aperture Radar data can be suitable and due to its sensitivity to land coverage, PolSAR has been used for the detection and mapping of landslides in forested areas. Nevertheless, investigation it is still needed for a consolidated evaluation of the most useful parameters and development of a reliable approach.

Purpose: In this paper, we explore the PolSAR potentialities to detect and map landslide affected areas by analyzing the large-scale landslide occurred on 9th January 2023 in the Pan-American Highway Corridor, kilometer 75, municipality of Rosas, Cauca (Colombia). Nearly 800 people have been directly affected by the landslide. Moreover, it caused several damages to crops, aqueducts, and the loss of support soil along a road segment of approximately 300 m, generating great economic losses and restriction of the connectivity.

Methods: In this work, data acquired by the satellite Sentinel-1 (Copernicus), with a dual polarization SAR system, have been used to derive several PolSAR products, H/α dual-pol decomposition (Entropy, Anisotropy and Alfa angle) and dual-pol vegetation index (DpRVI), comparing them before and after the studied landslide event.

Results: The landslide event causes a clear change in all calculated parameters. In general, the zone affected by the landslide shows a decrease in the mean entropy values and a consequent increase of the mean anisotropy values, with respect to the pre-event ones. The change of the entropy values in the affected zone reflects the change in the surface roughness, which is lower after the landslide occurrence due to a reduction of the vegetation coverage. For the alpha angle values, a decrease of the values is also observed in the affected area, corresponding to an intermediate dispeαrsion mechanism between the isotropic surface and the dipole volume. The values of the DpRVI index also show a decay in the mean values in the affected area. There is a combined dispersion mechanism that can be associated with a process of mass removal in development. Outside the affected area by landslide, all polarimetric indices remain almost unchanged.

Conclusions: The results of this case study show that the applicability of PolSAR techniques for landslide studies can be effectively applied for analysis of affected areas by landslide in tropical mountain regions. The potential of PolSAR techniques to detect landslide affectation in the analyzed roadway corridor is validated, since a clear change in all polarimetric parameters, has been detected. PolSAR approach provides useful basis for decision-making and roadway planning for disaster prevention and mitigation in high landslide-prone areas.

LANDSLIDE MONITORING WITH PASSIVE RFID: CASE STUDIES

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Purpose: We share our feedback on the first five implementations of landslide monitoring systems based on wireless passive RFID technologies (Le Breton et al., 2022, 2019).

Methods: The displacement is measured from the phase of the backscattering radiofrequency communication between a stable station and multiple passive tags on the landslide. Monitoring installation have been deployed from 2017 to 2023 on five landslides: Pont-Bourquin (Vaud, Switzerland), Harmalière (Isère, France), Valloire (Savoie, France), Villa Itxas Gaïana (Pyrénées-Atlantiques, France) and Châtel chairlift (Haute-Savoie, France).

Results: We show the measured displacement with reference data. We highlight the most extreme conditions: vegetation, rapid accelerations, cold, snowy and coastal winds. We also highlight the recent improvements on data processing reliability (Charléty et al., 2022a), localization (Charléty et al., 2022b), reading distance (up to 150 m) and automatization.

Conclusions: The passive RFID technique has monitored landslides on coasts and in mountains. It works for 100 to 200 m-long landslides that move more than 10 cm/year. That includes many landslides that need an early warning system. Its deployment is mostly comparable to a total station, which monitors numerous passive and low-cost targets. The total station works at higher distances and accuracy. The RFID works under harsher conditions: across vegetation, during snowfall, with frost and extreme cold, and during very rapid accelerations.

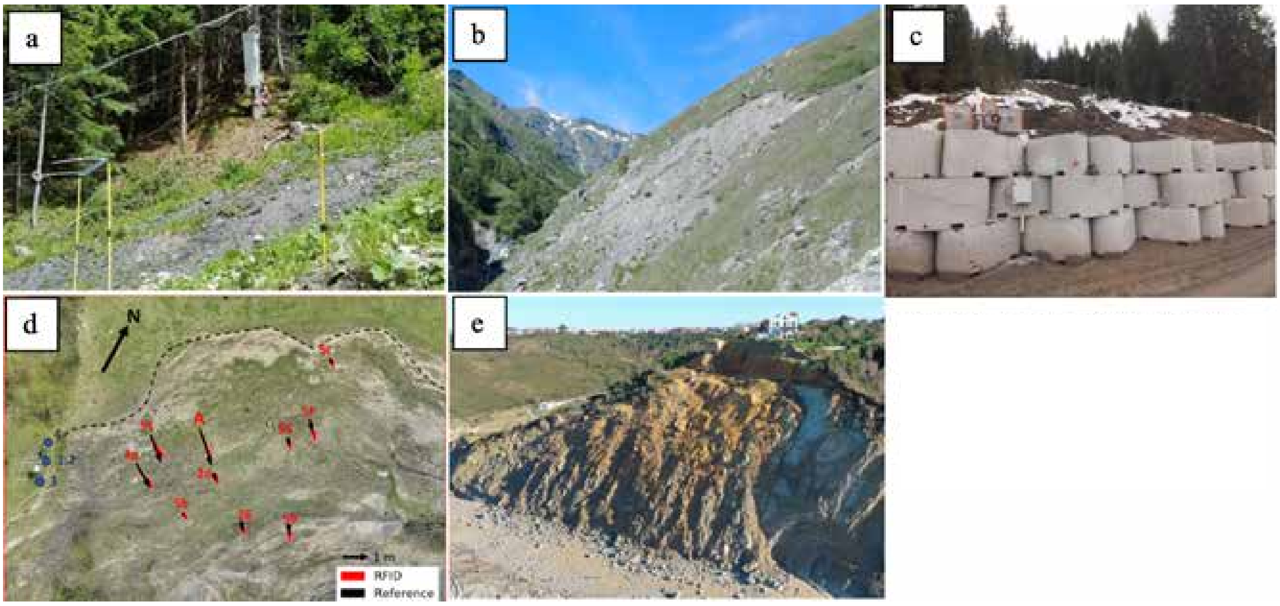

Fig. 1: Picture of the landslide monitered with an RFID system: a) Pont-Bourquin, b) Valloire, c) Châtel, D) Harmalière, e) Villa Villa Itxas Gaïana.

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Declaration of interest: The system has been patented (Baillet et al., 2018) and developed by Géolithe company and Université Grenoble Alpes, who sell and license it.

REMOTE SENSING OF VEGETATION COVERED LANDSLIDES USING MULTI-FREQUENCY SYNTHETIC APERTURE RADAR

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Purpose: Vegetation and snow cover are challenging situations when dealing with remote sensing landslide deformation measurement. The use of quasi-simultaneous multi-frequency radar measurements over landslides has great potential to provide safety in natural environment landslides. Such natural landslides are usually under vegetation or snow cover that influence, if not directly block, the interferometric measurement. It is well known [1] that the capacity of radio waves to penetrate on materials is highly dependent on the radio between wavelength and the electrical size of the objects. Focusing on landslides, in order to detect the terrain displacement occurring under the vegetation, it is necessary to use a wavelength comparatively larger than the type of vegetation wishing to overcome.

Methods: In order to solve this problem, authors have developed a multi-frequency GBSAR. It can work at five frequency bands X-Band, C-Band, S-Band, L-Band and P-Band. The system is an evolution of the first generation system developed by Amezaga et al. described in [2]. Accompanying the radar, an in-house DInSAR software has been developed to support the multi-frequency measurements. It allows estimating the terrain deformation via time series analysis of the interferograms. The system has been validated in field campaigns against slopes near Barcelona and the Catalan Pyrenees.

Results: Results from the measurement campaigns show coherent results with respect to the relation of vegetation height and signal wavelength.

Conclusions: The radar shows its capabilities to be used for landslide remote sensing. A potential contribution of soil moisture in the interferometric change difference is also detected.

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A STUDY ON THE APPLICABILITY OF SEDIMENT-RELATED DISASTER INVESTIGATIONS USING COMBINATIONS OF SATELLITE SAR IMAGES UNDER DIFFERENT OBSERVATION CONDITIONS

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Japan experiences numerous landslides disasters caused principally by heavy rainfall each year. It is not uncommon to see multi-jurisdictions be affected by disasters by a single concentrated rainfall event.

Rain-induced landslides occur in stormy weather conditions, under which aircraft investigations or optical satellite image analysis are not applicable at least for initial response phases. As a result, Japanese government has been tilted to use wide-area satellite SAR images, which can be conducted even in cloudy weather conditions for emergency response following the occurrence of disasters.

The satellite-based survey of landslide disasters in mountainous areas by way of SARs had previously been based on a comparative method namely those images taken sequentially prior and posterior to the events, under similar conditions in regard to the satellite used, the orbital linage, and observation angle. In many cases, paucity of pre-event library data (archive) result in irrelevantly outdated data, far too long prior to the disaster, resulting in numerous error factors such as forest logging impacts in the images, which significantly limit the relevance of the survey interpretations.

In this study, differential images were created using combinations of different observation angles or different SAR satellites. Prospective use of these images in rapidly surveying affected areas was verified by drawing them from a stock of image archives related to actual past disaster cases.

The verification method starts from a creation of differential images using pairs of different observation angles and different SAR satellites for landslides, subject to variety of sizes and shapes. These are obtained from affected slopes in different orientations. After that, the images were visually evaluated to assess their visibility. Additional differential analysis was performed on the same pairs to evaluate whether landslide movements could be accurately identified concomitantly.

Analysis of differential images using image pairs with different observation angles using L-band SAR (ALOS-2) showed that as long as the orbit is sufficiently close, minor difference of observation angles did not cause sizable difference in survey accuracy.

In the visual evaluation using combinations of different SAR satellites, it was found that the X-band SAR images had a marked advantage in identifying a long and narrow landslide movements in a valley, which had been deemed unfit by L-band SAR from the past experience.

On the other hand, in differential analysis using mixed wavelengths, it was confirmed that object identification using simple differential analysis was hard to obtain due to the large differences in the scattering patterns of X-band and L-band wavelengths.

As a result of these examinations, it is hinted that a constellation way, mixing sets of satellite SAR images, can be used for landslide disaster survey, where lack of past archive has been a major obstacle.

This may significantly reduce the requirement on pre-disaster event image library data. It can further facilitate the use of stable images from 1-2 months prior to an event. Also it may lessen various factors of misidentification, such as forest logging and land development in mountainous areas, a non-negligible source of erroneous identification.

ROCK SLOPE DISPLACEMENT AND CHANGE DETECTION ANALYSIS BY TERRESTRIAL PHOTOMONITORING IN WHITE CANYON, BRITISH COLUMBIA, CANADA

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Purpose: Landslide processes represent a significant threat to human life and infrastructure, particularly in mountainous regions. Accurate and continuous data collection in remote areas is essential for understanding these natural hazards, although often difficult to obtain. Remote sensing techniques have become increasingly popular in recent years to identify and map landslide processes. The purpose of this study is to use remote optical sensors to monitor active processes on the White Canyon cliff, an area located 275 kilometers northeast of Vancouver, BC, and at the Poggio Baldi Naltural Laboratory, an experimental site in Italy. The study aims to improve warning of events by continuously monitoring slope activity, reducing the consequence of failures and improving the safety of workers and infrastructure.

Methods: To monitor the active processes on the White Canyon cliff, a fully remote optical sensor with a resolution of 2Mp has been installed. This system takes photographs of a specific area at regular intervals, and the images are sent via GSM connection to a cloud system, where they are available to the operator. The IRIS software developed by Nhazca Srl, a startup of Sapienza University of Rome, enables the evaluation of changes occurring on the slope and the measurement of debris movement within channels, through the analysis of photos. The same monitoring technique has been tested and implemented successfully at the Natural Laboratory of Poggio Baldi, an experimental site of the Department of Earth Science of Sapienza, to study rockfall processes through a multi-sensor approach. The Poggio Baldi site permitted the team to calibrate the use of the system and optimize the analysis, which was then applied to the White Canyon site.

Results: After five months of monitoring activities in White Canyon, the preliminary results show that the remote optical sensor is successful in detecting and measuring debris movements within channels. The data collected from the photographs were used to identify changes occurring on the slope, including rockfall events and debris movements. These data are critical in understanding the active processes on the cliff, and they enable continuous remote monitoring of the deformation process. The results also demonstrate the potential of the PhotoMonitoring technique as a low-cost and effective method for monitoring landslide processes in remote areas. It should be noted that some challenges were encountered caused by loss of power during very cold winter temperatures, and by changing weather conditions including fog and snow.

Conclusions: In conclusion, this study demonstrates the potential of remote optical sensors and the PhotoMonitoring technique in monitoring active landslide processes in remote areas. The PhotoMonitoring technique is a low-cost and effective method for continuous remote monitoring of deformation processes. Future studies can expand the use of this technique to other remote areas and investigate the applicability of this method for detecting and monitoring other natural hazards.

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MULTIVARIATE STATISTICAL ANALYSIS OF THE CONDITIONING FACTORS FOR LANDSLIDES IN THE CENTRAL AREA OF ANGRA DOS REIS, RIO DE JANEIRO STATE, BRAZIL

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Purpose: This study aims to analyze landslides conditioning variables (LCV) in Angra dos Reis city, Rio de Janeiro State, Brazil (Figure 1). It was done by remote sensing techniques, geoprocessing, and multivariate statistical analysis to determine those factors that have the most influence for future application in the landslide susceptibility models.

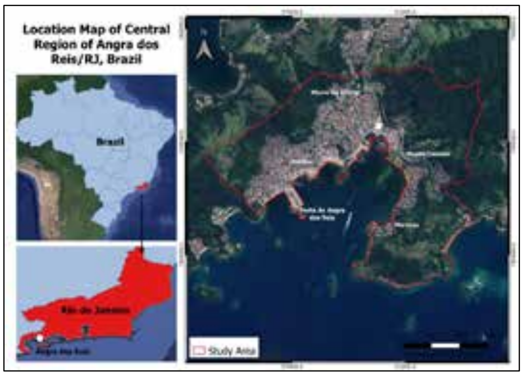

Fig. 1: Study area.

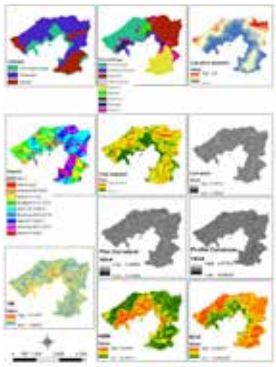

Fig. 2: Conditioning variables.

Methods: The LCV data shown in Figure 2 were preselected based on recent literature (Canavessi et. al., 2020; Huang et al., 2022). The elevation, slope, curvature, aspect, topographic wetness index (TWI), vegetation cover (NDVI), and urban occupation (NDBI) were calculated using ArcMap 10.5 software, which utilized a Copernicus DEM model and Landsat 8 images. Lithology and geomorphology data were obtained from Coelho Netto et al., 2014. Landslide data from 2010 to 2021 (Figure 3) were collected using the Google Earth platform and combined with landslide reports from the local Civil Defense. Statistical analysis was performed on the Google Colab Platform, with data normalization and Python Scikit-Learn Principal Component Analysis (PCA) applied to a 30-meter resolution grid.

Fig. 3: Landslides occurrences.

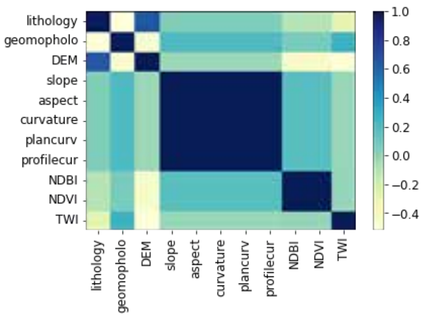

Fig. 4: Correlation matrix.

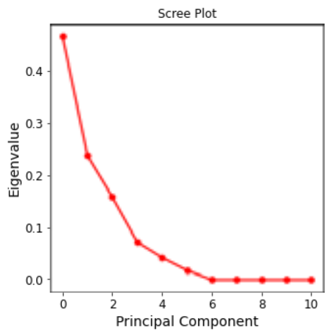

Fig. 5: Scree plot graph.

Results: The first part of PCA's analysis involved calculating the covariance matrix (Figure 4), denoting a strong positive relationship between slope, aspect, curvature, plan curvature and profile curvature; NDVI and NDBI. The second part was to define the number of principal variables to reduce the model's dimensionality defined through the calculation of the Eigenvalue in a Scree Plot graph (Figure 5) for each LCV, so that the higher the Eigenvalue, the greater the importance. The results show that only six out of eleven variables were necessary to explain at least 95% of the model's variability. Furthermore, TWI, NDBI and slope have shown to be the most important variables in the triggering of landslides, while the terrain's elevation (in meters) and profile curvature have presented less importance.

Conclusions: The study combined remote sensing and geoprocessing techniques to develop a landslide inventory map and identify critical factors using machine learning. The results provide input data for susceptibility models and provide spatial correlations between landslide occurrence and conditioning factors, identifying the most critical factors of the studied area.

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SMART BOULDERS FOR REAL-TIME DETECTION OF HAZARDOUS MOVEMENT ON LANDSLIDES

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Purpose: Landslides are a major hazard along coasts and in mountain regions in the UK and globally, causing disruption, fatalities and severe economic loss. Landslides can also propagate downslope in the form of debris flows and even interact with floods to cause a cascade of hazards. Landslides and related hazard cascades are increasing under climate change and increasing population pressure. This makes monitoring and early warning of slope instability and landslides increasingly vital to mitigate their impacts. The aim of this research is to develop effective real-time monitoring of a range of landslide hazards in coastal and mountainous environments of the UK and France using novel sensor technologies, and validate machine learning models to detect hazardous movement for early warning.

Methods: On the UKRI-funded SENSUM project (smart SENSing of landscapes Undergoing hazardous hydrogeomorphic Movement), we have leveraged advances in micro-electronics and Internet of Things technologies to develop a low-power motion sensor that communicates via Long-Range Wide Area Network (LoRaWAN). A sensor includes a GNSS receiver and inertial measurement unit (accelerometers, gyroscopes and magnetometers) and motion-based power management allows the sensors to run from batteries for long periods. The devices were designed to be embedded in natural or manmade boulders (SlideCubes), cobbles and wood debris within landslide and flood-prone settings in sites within the UK and France. The sensor was intended to capture unique data on motion from inside landslides and floods. This data combined with ground-truth GPS and drone surveys alongside controlled laboratory tests, provides training and validation for machine learning algorithms in generation of hazardous movement early warnings.

Results: The sensors were deployed at several sites, with around 20 devices at each, forming Wireless Sensor Networks that also consist of locally-installed LoRaWAN gateways and also incorporating other equipment such as soil moisture sensors and discharge gauges. With refinement to the approaches used deployment was practical and straightforward and communication reliable. Motion and general status data were successfully relayed to the cloud for storage and visualization on our server. Most sensors were able to be recovered without problems for battery replacement and redeployment. We present sensor data on movement of landslide complexes at the Isle of Wight and Lyme Regis and preliminary data from the Hermaliere landslide in France. We demonstrate how machine learning can be used to detect and characterize sensor movement, including their potential to differentiate between sliding and rolling behaviour validated from laboratory testing. Finally, we discuss how machine learning may be used to provide alerts of hazardous movement within an early warning system.

Conclusions: We conclude that the sensors developed show potential as an early warning system for landslides and flooding. Deployment of the system in landslide and flood-prone areas is shown to be simple and robust, providing near real-time motion data to the cloud. Machine learning is shown to successfully identify motion types, with potential to extend the system to provide early warning alerts of hazards.

SESSION 5.4

WILDFIRE, EROSION AND LANDSLIDE IN THE FRAMEWORK OF GLOBAL WARMING: CIVIL PROTECTION AND LAND MANAGEMENT AIMED AT MITIGATION OF EFFECTS ON SLOPES INDUCED BY EXTREME EVENTS

POST-FIRE ANALYSIS AFTER THE 2018 EVENT IN MONTE PISANO MOUNTAIN (TUSCANY, ITALY): MONITORING AND PLANNING OF MEASURES AT HILLSPLOPE SCALE TO MITIGATE EROSION PROCESSES

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Frequent wildfires and hydrological instability are in a close relationship of cause and effect and both have a historical importance in most of the Mediterranean basin, especially in Italy, due to the lack of structural interventions and proper management. The present study focuses on the monitoring of post wildfire rehabilitation treatments executed immediately after the last fire event in the Monte Pisano region, Tuscany, Italy. The aim is to suggest improvements and to develop a replicable methodology that could facilitate the design of future plannings.

Works of interest have been selected on GIS cartography, then surveyed on field as a reproof. The data collected are helpful to assess the functionality of interventions through hydrological modeling. A Lidar flight was done about two months after the wildfire, and a cloud point was produced. By means of a special software, a DTM was processed from the cloud point. The works, from the regional plan and before being surveyed, were rasterized and modeled on the DTM. The hydrological modeling was set, in order to obtain maps showing the runoff behavior, in both terms of accumulation and direction and in the cases with works and on smooth terrain. Finally the maps are compared through the RPII index, which allows to see the preferential runoff roads, highlighting areas with a major drainage alteration and so, potentially, more prone to soil erosion.

The final result of this study allows us to enhance the planning of the restoration works in order to make them more effective and efficient: the general conditions were good, but in one case a great flow accumulation was predicted by the model, in a risk area, with a house, a street and an olive field. Therefore, in the final part Risk mitigation action hypothesis, a new work, a ditch, is proposed and modeled according to RPII comparison results. In addition, the data field collected would be useful in the future to deepen a special study on forestry planning choices.

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EVALUATION OF THE RUSLE MODEL FOR QUANTIFYING HILLSLOPE EROSION AFTER THE WILDFIRE, ON MARCH 30, 2020, IN XICHANG, CHINA

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Purpose: Wildfires greatly aggravate hillslope erosion in the forest area and induce many secondary disasters, with far-reaching effects on the landscape and ecosystem. So quantization and prediction of hillslope erosion in the burned areas have been the major concern to land managers, which can contribute to the emergency response to post-fire disasters and efficient ecological restoration after the wildfire. The Revised Universal Soil Loss Equation (RUSLE) is one of the most widely used models for estimating soil erosion. The purpose of this study is to evaluate the performance of the RUSLE model in the burned area at the hillslope scale and the watershed scale, based on a devastating wildfire with burning more than 3000 ha of forest on March 30, 2020, in Xichang, Southwestern China.

Methods: A series of required variables were computed based on remote sensing interpretation and field tests and input into RUSLE to estimate the hillslope erosion rate. Then the sediment yield at the watershed scale was calculated combined with the Sediment Delivery Ratio (SDR) model. The performance of the RUSLE was evaluated against another research in this area which developed an empirical model with great performance based on the field-measured data.

Results: Wildfires can dramatically deteriorate surface soil properties. The dry density of the surface soil is negatively correlated with fire severity. The organic matter content shows little change between unburned and high-severity class areas while increasing by 61.6% and 27% in low and moderate severity class areas, respectively. For soil particle distribution, the clay content shows no significant difference, while the silt content has positive but the sand content has negative correlation with fire severity. Consequently, the soil erodibility in moderate and high severity class areas significantly increases compared with unburned and low severity class areas. The RUSLE-derived total quantity of hillslope erosion in the study area is 33.3×104 Mg (24.7×104 m3), of which the mean hillslope erosion rate in the unburned, low, moderate, and high severity class areas is 4.7 Mg/ha (0.3 mm), 34.6 Mg/ha (2.5 mm), 85.8 Mg/ha (6.5 mm), 180.0 Mg/ha (13.2 mm), respectively. In addition, combined with the SDR model, we estimated the quantity of sediment transported to the outlet of each sub-watershed in the study area. In the first rainy season after the fire, a total of 14.4×104 Mg (10.7×104 m3) sediment was mobilized to the specified destination in the study area, while practically 11.6×104 m3 sediment was produced by post-fire debris flow occurred.

Conclusions: Compared with the aforementioned existing study, the RUSLE shows acceptable performance at the hillslope scale in the burned area. Since other source materials (such as landslides, collapse, and channel sediment) were involved in debris flow, it is deduced that the RUSLE combined with an appropriate SDR model also shows satisfactory performance at the watershed scale and the feasibility of application in post-fire debris flows.

QUANTIFYING THE FACTOR CONTRIBUTION ON SHEAR STRENGTH OF SOIL AUGMENTED WITH NATURAL FIBERS FOR EROSION PREVENTION

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Purpose: Soil erosion is a major environmental problem which can lead to landslide as it weakens the stability of slopes and hillsides. One of the solutions to stabilize the soil is by increasing the shear strength of the soil. The contribution of natural fibers in the improvement of shear strength of soil has received a lot of attention in recent years as a nature-based solution because of its sustainability and cost-effectiveness. Hence, the objective of the current study is to determine the effectiveness of fiber-soil parameters in enhancing the shear strength of the soil at surface level for prevention of erosion.

Methods: Direct shear tests were conducted on the soil-fiber specimens with different soil type, fiber type, fiber content and soil moisture content. For the experimentation, a fractional factorial planning method, Taguchi Method, has been adopted. Further, statistical analysis has been performed to obtain the factor contribution and optimum level of each parameter.

Results: The results obtained indicate the overall dominance of fiber content followed by the soil type on the shear strength of soil. The types of soil, the type of fibers, and moisture absorption capacity of fibers also have a considerable effect on the shear strength of the soil. In addition, the shear strength of the soil and fiber-matrix increases when the moisture content is on the lower side of optimum moisture content and decreases when the moisture content is on the higher side of optimum moisture content.

Conclusions: Based on the result obtained it can be concluded that the fibers have significant effect on enhancing the shear strength of the soil. Such studies can reinforce the option of soil-fiber to mitigate the surface erosion till shallow depths.

WILDFIRE-CONDITIONED-LANDSLIDE SCENARIOS UNDER MULTI-HZARD PERSPECTIVE: EXPERIENCES FROM THE URBAN AREA OF NAPLES (ITALY)

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Purpose: Landslides are an indirect effect of earthquakes or heavy rainfall triggers but are typically favoured by a combination of static predisposing and dynamic preparatory factors, among which the anthropic impact is one of the most effective. Among the most relevant preparatory factors for shallow landslides and debris flows mechanisms, is the occurrence of wildfires, that are retained responsible for changes in the hydrologic and geomorphic response of watersheds. Moreover, wildfires cause the denudation of hillslopes and the consequent decline of root strength, that contributes significantly to stability. In the here presented research, multi-hazard scenarios considering degree of saturation of soil covers and earthquakes as triggering factors was depicted, evaluating, for earth sliding, the stabilisation contribution of root cohesion to infer the role of wildfires as a preparatory factor for landslides.

Methods: The method used is PARSIFAL (Probabilistic Approach for Rating Seismically Induced slope FAiLures), a probabilistic multi-hazard tool which includes in a three steps procedure: 1) susceptibility analysis including differentiated approach for rock and earth failure mechanisms; 2) slope stability analysis; 3) synthetic mapping of generated scenarios, based on grid or slope units. It was employed in three areas of the Metropolitan City of Naples: the Cumae Mount and the hills of Camaldoli and Agnano, that experienced diffused rockfalls and shallow instabilities, and also suffered frequent wildfires. Study sites are featured by a dense population and a high archaeological value that pose significant risk conditions.

Results: Results provided landslide scenarios under seismic trigger featured by a RP of 475 years and dry or partially saturated conditions, showing landslide triggering probability within compatible slope units. The spatial convergence between potential source areas and landslides inventoried proved the validity of the obtained results. The influence of wildfires significantly increased the earthquake-induced landslide susceptibility in the Camaldoli hillslopes, confirming their importance on slope stability and highlighting their role as preparatory factor for earth sliding.

Conclusions: The here mentioned study is going to be implemented with back analysis of firing events, that will be modelled through multispectral remote sensing and optical images change detection analysis aimed at the reconstruction of the levels of severity of the wildfire and the compilation of landslide effects inventory. The effect of wildfires over different time period will be considered, weighting vegetation loss during the event and monitoring the hillslope denudation process in the following years. The alteration of mechanical properties of rocks and soils could be also investigated, as well as the influence of wildfire propagation. Most of these concepts are being studied from Sapienza in the FIRE project (wildFire-related-landslide scenarIos for territorial planning and Risk managEment), that aims to provide an innovative contribution to the construction of quantitative probabilistic scenarios of slope instabilities, also in view of defining best practices for fire extinguishing and for land management plans with respect to the potential damage caused by fires.

EFFECT OF FIRE-INDUCED SOIL WATER REPELLENCY ON SLOPE STABILITY IN A FIRE DAMAGED FOREST

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Purpose: The frequency and intensity of forest fires have recently increased due to climate change. Forest fires can cause severe damages to the environment and threaten human lives and livelihoods. Fire significantly affect several chemical, physical, and microbiological properties of the underlying soils. During a fire, combustion of litter and soil organic matter can enhance soil water repellency in a forest watershed. Various studies have been conducted to examine the effects of fire on soil physical and chemical properties over the past decades, but less attention has been paid to the effect of soil water repellency on slope stability after fires.

Methods: This study was conducted to examine the effect of fire-induced soil water repellency on slope stability in a mountain watershed using the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis (TRIGRS). The Andong area in the Republic of Korea, which was burned by the forest fire on Feb. 2021, was selected for modeling purpose. The soil water repellency and associated saturated hydraulic conductivity was measured since the 2021 fire, according to the burn severity. The fire damage was classified into four categories: crown-fuel consumption, foliage necrosis, surface-fuel consumption, and unburned. As an input to the TRIGRS, topographic data was derived from 10 m digital elevation model (DEM), and soil characteristics were extracted from the forest soil map.

Results: The soil saturated hydraulic conductivity decreased with the burn severity, being the lowest in the crown-fuel consumption site and highest in the unburned site. The results of TRIGRS indicated that the average factor of safety (FS) reached the same value as the rainfall duration increased, but decreased slowly as the fire damage intensified under all rainfall conditions

Conclusions: During a fire, the combustion of organic matter can release volatile hydrophobic substances, which may develop hydrophobicity in soils. The fire-induced water repellency can prevent water from infiltrating soils and thus reduce the potential risk of landslide. However, we expect that the unstable sloping area can gradually expanded 2-3 years after a fire due to increases in effective rainfall and reduction of tree root strength. This study highlights the relationship between water repellency and slope stability in a fire damaged forest after a fire.

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DYNAMIC LANDSLIDE HAZARD EVALUATION IN THE CONTEXT OF WILDFIRES AND CLIMATE CHANGE IN THE MEDITERRANEAN AREA

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The Mediterranean area is known to be a hotspot for Climate Change, especially regarding the precipitation and temperature extremes projected for the future in the different scenarios. Along with these changes characterized by longer dry periods, wildfires hazard dramatically rises, exposing wide areas to weathering and increasing the potential soil erosion.

The evaluation of the landslide hazard cannot disregard such projections, leading to the study of new methodologies for a dynamic hazard evaluation under climate change conditions. Sardinia island is particularly prone to landslides, with almost the 27% of territory falling in landslide hazard (6474.4 km2 over 24099 km2), the 25% of which (1648,3 km2) falling in high and very high landslide hazard. The studied area, named Montiferru (West Sardinia), in July 2021 was involved in a dramatic wildfire that devastated 13,000 hectares, falling in the category of Extreme Wildfire Events (EWEs). After a significant rainfall event in November 2021, for the first time, rockfalls were recorded in a previously forested area, posing the attention for a new approach to landslide hazard evaluation.

A multi-model approach combined with field analysis was used for this study, aimed at evaluating how the wildfire (EWE) changed the soil properties and, by consequence, the landslide hazard. Soil properties from laboratory tests, such as granulometry, particle weight, density, specific gravity, Atterberg limits and shear test, were compared between burned and undamaged areas. In addition, in-site soil infiltration tests were carried out. Physical data were implemented in SWAT (Soil and Water Assessment Tool) for the simulation of runoff and erosion and Rockyfor3D was used for the rockfall simulations, comparing scenarios before and after the wildfire.

Soil properties in burned areas, such as liquid and plastic limit, were found to be generally worst if compared to undamaged areas, increasing the susceptibility to mud flows. Infiltration rate is lower in burned soils, due to the formation of a thin layer of ashes in the surficial soil profile, which reduces hydraulic conductivity of soils, possibly causing an increase of surface runoff. Accordingly, results of SWAT simulations showed that surface runoff increased after the EWE, together with erosion and sentiment transport, mainly occurring via channel erosion. Rockfall simulations showed that, in the burned areas, the lack of vegetation could increase the kinetic energy, runout and, by consequence, the hazard. Such effect is more evident in smooth slopes than in rough slopes interested by scree and boulders.

The next challenge will be to implement this setup with future climate data, to simulate how Climate Change could further affect the landslide hazard and wildfire risk in the future, evaluating mitigation scenarios and focusing on the changes in hazard patterns. Results of the study highlight that assessment of landslide hazard should be a dynamic process, requiring a priori evaluation of different scenarios, considering climate and land cover changes (i.e., the EWE), mostly where soil properties are crucial features.

WILDFIRE- INDUCED GEOHYDROLOGICAL HAZARDS IN THE ALPS: THE NEED FOR A SYSTEMATIC DOCUMENTATION PROCEDURE

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The increase in heat waves and droughts caused by climate change leads to a high risk of wildfires in the Alps both in terms of frequency and intensity, which eventually make the landscape more susceptible towards geohydrological processes. Climatic extreme events such as storms (e.g., hail and heavy precipitation, snowy winters) additionally weaken the forest condition/structure after a severe wildfire and lead to an aggravation of the consequences (Figure 1). The susceptibility to wildfire and geological disposition to erosion or gravitational mass movements during and after a wildfire depends on a variety of factors that may be mutually dependent.

Little research and initiatives focused so far on the occurrence of fire-induced geohydrological processes in the Alps (e.g., Conedera et al., 2003; Providoli et al., 2002; Melzner et al., 2019; Melzner et al., 2022; Melzner, et al. 2023).

The present study summarizes the effects of wildfires in different geological settings in the Alps focusing on the factors influencing the geohydrological hazard in the course of and after a wildfire event and to provide incentives for further research.

This forms the basis for recommendations to modern fire management activities in terms of a systematic documentation of geohydrological processes during and after a wildfire event and the related parameters, which should be integrated into national fire databases and data information systems.

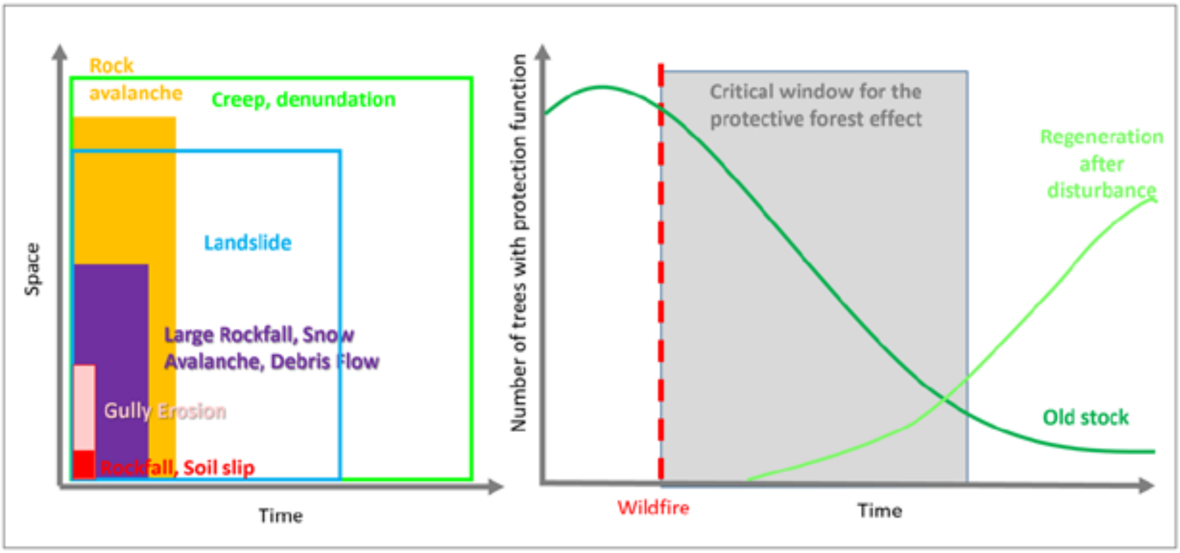

Fig. 1: Critical time window for the protective effect of forest stands against geohydrological natural hazards after a severe wildfire (Melzner et al., 2023).

In particular, there is a practical need to verify/understand and possibly quantify the impacts of wildfires to rock and soil surface in order to improve the capability to predict and possibly tackle fire-induced geohydrological processes and the associated hazard and risk levels.

Studies on the fire ecology of the Alpine tree species and the analysis of the long-term effects of fire and other climatic extremes on future rockfalls, landslides, debris flows, and erosion disposition are thus important research topics for the future.

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LANDFORMS AND GEOMORPHIC CONTROL ON POST-FIRE EROSION: THE MONTIFERRU STUDY-CASE

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Purpose: Wildfires dramatically impact hydrology and soil properties and consequently change soil erosion due to rainfall. Enhanced sediment availability due to erosion (rill, rainsplash and sheetwash) and post-fire soil sealing generate diffuse surface runoff and debris flows. Specific post-fire hydrological and erosional responses in volcanic terrains were investigated in the Montiferru Area (W Sardinia, Italy). The study area is a volcanic complex, dominated by lava domes, flows and ignimbrites of Miocene to Pliocene age, with variable morphology and soil cover. Many of the soils covering the area are highly erodible andosols, which stability on steep slopes is allowed only by the vegetation cover. The high erodibility of these soils is due to the sandy texture, the poorly developed structure, and the high porosity of the upper horizons. This region was affected by an impressive wildfire in July 2021, when about 20.000 hectares of forest grown in first-order catchments, olive groves and shrublands, were burnt in just 8 hours (as per the civil protection records, the wildfire affecting the forested area lasted for possibly more than 48 hours, the overall event went on for 8 days no-stop) The lithological homogeneity of many catchments makes the Montiferru area an ideal study case for understanding the role of geomorphological factors in post-fire erosion processes.

Methods: We conducted field surveys immediately after the fire and are still following the evolution of surface processes over time. The field studies were combined with analysis of pre-fire orthophotos, satellite images and post-fire high-resolution multispectral images recorded 9 months after the event, to list and characterise both old and new landforms. The study revealed diffuse and local processes and estimated the volume of remobilised material in 2021-2023.

Results: Windstorms occurred in the three months after the wildfire moved ash between the burned catchments, generating plumes. On November 2021 the first rainstorm occurred and, a mudflow composed mainly of ash covered a 12-km path. Networks of small rills developed in eluvial products and soils, whereas sheetwash erosion occurred on the colluvial deposits. New landforms formed, previously absent in the area: large rills cutting the slopes, sometimes even following paths; plunge pools; enhanced lateral and vertical erosion of channels, associated with the passage of the debris flows. Boulder-rich fans and levees are unique depositional landforms in the catchments and collect most of the sediment. Cobble-rich secondary deposits have also been found on the slopes.

Conclusions: Overland flow processes have displaced material from the slopes and channel area, generating mudflows and debris flows in a process of progressive sediment bulking. By winter, a year after the wildfire, the vegetation had partially recovered and some erosional processes had already been halted. Vegetation played a primary role in erosional processes and in controlling the impact of the wildfire: geomorphologically similar catchments with different rates of vegetation recovery show distinct landform evolution and development. The measures taken on the landforms will allow us to estimate the volume of the eroded material and to evaluate the hazard levels of post-fire overland flow processes.

SOIL BIOENGINEERING TECHNIQUES TO COUNTERACT SOIL EROSION IN FIRE-AFFECTED AREAS

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Purpose: Post-fire erosion represents one of the most important threats which affect soils after wildfires. This work aims at identifying areas at risk of erosion, considering predisposing factors such as slope, soil type and fire severity and to assess the effect of different types of soil bioengineering works in reducing soil erosion and in promoting the re-naturalization of the area.

Methods: To identify the areas object of the study, a survey (databases of the Civil Protection - Puglia Region and Carabinieri Forestali), was carried out. Clay soils and slope > 20% were considered as inducing factors. N. 30 large areas affected by fire on slopes in the last 5 years were selected. Subsequently, a cadastral and an in-field survey was carried out to finally select the study area ("Bosco Difesa Grande" of Gravina in Puglia). N. 2 sites, were further identified considering the year of the fire event (2017) and the fire severity. Here some soil bioengineering works were implemented and to monitor the effect of the works on the re-naturalization of the area, both a field and a remote sensing survey were carried out.

Results: Soil bioengineering works were carried out in winter 2023 in the two intervention sites. Death and weed plants were removed from both sites. A wattle was built first fixing the vertical poles and then superimposing and fixing the rods by means of nails. The palisade also was built first fixing the vertical poles and then fixing the horizontal poles. Autochthonous vegetation species were planted in the two sites (Quercus pubescens Willd, Q. ilex, Fraxinus ornus L., Acer monspessulanum L., Sorbus domestica L., Crataegus monogyna, Pistacia lentiscus L., Rhamnus alaternus L., Prunus spinosa L., Phillyrea latifolia L.). To assess the effect, in terms of reduction of soil erosion and re-naturalization of the area, of the two technical solutions the monitoring was carried out comparing the areas in which the interventions were realized with adjacent areas in which no interventions were implemented.

Conclusions: The described methodology is useful to identify areas in which prioritize intervention after fires of medium or high intensity. The monitoring of the pilot soil bioengineering works, within the selected areas, will widen the information relative to the growth of the species and the efficacy of the soil bioengineering technical solutions used in the restoration of slopes after the fire occurrence.

EFFECTS OF THE TEMPORAL DYNAMIC OF ROOT REINFORCEMENT AFTER WILDFIRE ON THE SUSCEPTIBILITY OF SHALLOW LANDSLIDES

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The temporal dynamic of root reinforcement after wildfire is decisive for the increase of shallow landslide probability. The quantification of the dynamic of root reinforcement after wildfires is important for both, assessing the increased hazards due to shallow landslides and the planning as well as the prioritization of measures to mitigate the risks. The difficulties in quantify root reinforcement dynamic are in particular related to the characterization of the fire intensity and severity, the prediction of the resistance and resilience of the vegetation and the combined effects of factors influencing root reinforcement such as soil type and climatic conditions.

In this contribution we combined methods to calculate the dynamic of root reinforcement (decay and recovery) with a hydro-mechanical slope stability model (SlideforNET) to calculate the cumulative probability of shallow landslides after wildfires. Considering the case study of a wildfire in the commune of Meiringen (Switzerland) we present how modeling results can be used to assess the increased hazards of shallow landslides and differentiate the prioritization of biological and technical measures to mitigates risks.

Our calculations yield that the cumulated probability of shallow landslide may increase up to 90 percent within the next 100 years after the wildfire due to the gap in root reinforcement that occurs from fast decay and slow regeneration. Meanwhile the cumulated probability of shallow landslide may still decrease up to 30 percent within the next 100 years if the regeneration is successful. The contribution of root reinforcement dynamic on the cumulated probability depends on the slope angle and is negligible for very steep slopes (greater than 40 degree) as well as for more flat slopes (lesser than 25 degree).

Based on these results we conclude that the following prioritizations should be made. In areas with a slope angle close to the friction angle (in this case 35 degree), biological measures may effectively contribute to the long term protection against shallow landslide and reforestation should be supported. In more steep areas, technical measures should be applied to mitigate the hazard and also to protect the reforestation until its root reinforcement is strong enough to provide a sufficient protection.

SESSION 4.2

SPATIAL LANDSLIDE ASSESMENTS AND BEYOND: NEW HALLENGES IN MAPPING, MODELLING, VALIDATION AND SCENARIO BUILDING (part II)

TOPOGRAPHICAL ANALYSIS ON THE COLLAPSING LANDSLIDES INDUCED BY RAINFALL - CASE OF THE 1972 AMAKUSA DISASTER IN KYUSHU, JAPAN

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Purpose: Cuesta terrains are susceptible to translational slides on back slopes as well as rockfall and small slump-type slides on escarpment slopes. A complex landslide consisting of a primary slide on gentle slopes with a dip of less than 30° and subsequent movement of disrupted materials has been reported frequently in recent a few decades in Japan. Most of sliding materials run out from the source area. We call such landslide as collapsing landslide hereafter. Since a discontinuity plane such as a layer boundary and bedding planes tends to feature a slip surface, cuesta terrains seem to be prone to collapsing landslides. Therefore, we conducted topographical analysis on the collapsing landslides which occurred in the cuesta terrain of the Amakusa Islands, Kyushu, Western Japan in 1972.

Methods: The study area of 100 km2 including 15 cases of collapsing landslides consists of Cretaceus and Paleogene sandstones and mudstones of marine origin. Those layers predominantly feature homoclinal structures dipping 10°-30° in NW direction except the small area along the NNE-SSW anticline. In this study, gradient, orientation of the slopes of the collapsing landslide and the whole study area is extracted. Since the landslides have elongated features with the source areas of 10,000-20,000 m2 and their width is slightly larger than 50 m, a 50 m DEM resized from the 10 m DEM prepared by the Geospatial Information Authority of Japan is used.

Results: Figure1 shows dip and orientation of the slopes in each 50 m mesh in the whole area and the source area of collapsing landslides. A catchment area of the landslide is also shown. It is inferred that concentrated dots of 75° -195° (clockwise counting from N) in slope orientation and of steeper slopes than others might indicate the escarpment slopes of cuesta terrain. Similarly, those of 270°-345° in slope orientation and of gentler slopes might indicate the back slopes. Most of the collapsing landslides are classified into steeper ones with the dip of 15°-30°in the former group and gentler ones with that of 10°-30° in latter. Based on these results, a distribution map of slopes with the above gradient and orientation is prepared from the 50 m DEM. It reveals that most collapsing landslides are located on either escarpment slopes or back slopes.

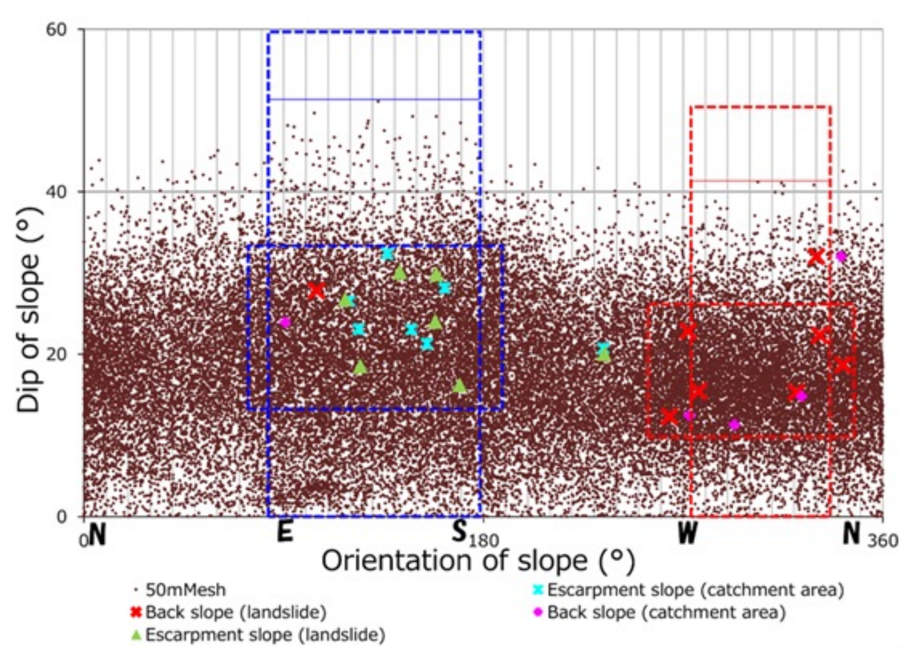

Fig. 1: Dip and orientation of the slopes (each 50 m mesh) in the collapsing landslides and the whole study area.

Conclusions: Dip and orientation of the slopes reflect geological structures of the cuesta terrain which caused the initiation of collapsing landslides during the 1972 Amakusa disaster. DEM-based topographical analysis is useful for landslide susceptibility mapping in cuesta terrains.

LANDSLIDES, GULLY EROSION AND BADLANDS AS ASSOCIATED GEOLOGICAL HAZARDS IN FLYSCH ENVIRONMENT - ANALYSIS OF GEOMORPHOLOGICAL INVENTORIES AND LIDAR DTM AT A LARGE SCALE

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Purpose: Central part of Istrian Peninsula (Croatia) is composed of Eocene flysch sediments, with predominantly marls and sandstones in alternation. The study area (19.96 km2) comprises the part of the City of Buzet, where weathering processes and high erodibility of mechanically weak bedrock led to the formation of erosional features and numerous landslides. Despite to their significant impact on the environment and elements at risk, detailed mapping, and study of the relationship between the soil erosion and sliding processes have never been performed before. Acquisition of the high-resolution remote sensing data that effectively enable such research is performed in the frame of the scientific research project "Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology" (LandSlidePlan, HRZZ IP-2019-04-9900), funded by the Croatian Science Foundation. The 0.3 m airborne LiDAR (Light Detection and Ranging) digital terrain model (DTM) was used to identify and map landslides, gullies, and badlands at a large scale. The purposes of this research are: (i) to create the first detailed geomorphological inventories of landslides, gullies, and badlands in flysch deposits of Central Istria by using high-resolution airborne LiDAR data; (ii) to determine typical geomorphological settings of landslides; and (iii) to qualitatively determine the spatial relationship between the landslide and soil erosion phenomena, i.e., gullies, and badlands at the selected representative portions of the study area.

Methods: Airborne laser scanning was performed in March 2020, with an average point density of 16 pt/m2. Topographic datasets were derived from the 0.3 m bare-earth LiDAR DTM and visually interpreted: (i) hillshade map; (ii) slope map; (iii) contour map; (iv) topographic roughness map; and (v) stream power index map. Visual identification and mapping of landslides, gullies, and badlands were performed at a large scale (> 1:500). Badlands were first identified on orthophoto images at 0.5 m resolution, and subsequently mapped on LiDAR datasets.

Results: In this study, three detailed geomorphological inventory maps are created: (i) the landslide inventory map, comprising 1 164 landslides; (ii) the gully inventory map, comprising 337 gullies; and (iii) the badland inventory map, comprising > 200 badlands. Predominant landslide types are slides, and slide-flows. Landslides are mostly shallow, and very small to small. They generally occur in three typical environments: (i) within complex gullies (approx. 65 % of landslides), (ii) along agricultural terraces, (iii) and on artificial slopes along the roads. On the other hand, landslide phenomena within badlands are sporadical.

Conclusion: In this study, first geomorphological landslide and soil erosion inventory maps in flysch environment of Central Istria are produced at a large scale by using high-resolution LiDAR datasets. Strong relationship between gully erosion and sliding processes determine the geomorphological settings, types, and geometry of most of the landslides. It is considered that the inventories can significantly contribute to the sustainable land management in the study area, and also for estimating temporal changes in gully erosion. Moreover, in the future research, the results will be used to test the relevance of gullies and badlands as landslide conditioning factors in landslide susceptibility modelling at a large scale.

NATIONAL SCALE LANDSLIDE SUSCEPTIBILITY ASSESSMENT IN GREECE: A PROJECT IN PROGRESS

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Purpose: The current work figures out an approach to estimate landslide susceptibility in Greece. This is the first study to undertake the updated official National Geodatabase of Landslides covering the entire country for landslide susceptibility assessment. This research recognizes the critical role played by scale for landslide susceptibility modelling. Therefore, part of the aim of this work is to use the minimum, yet sufficient data required to develop more versatile, generalized regional susceptibility models (medium scale), that can then be used as indicators for national scale (small scale) analysis.

Methods: The proposed method investigates four (4) well-known annually suffering landslide prone areas, with the principal distinction drawn on the composition of the geological formations. The inventory includes more than 5000 landslides around the national territory while in the selected areas the landslides represent approximately 5% of it. The historical archives include landslide locations, timing of landslide events, landslide type, triggering factors, as well as the impact of each landslide, where such information is available. However, this data contains a level of uncertainty about the geospatial accuracy, that depends on the age of the report. For that reason, information was evaluated by field reconnaissance surveys at the selected regions during the last four years, to increase the accuracy and the reliability of the inventory as well as the landslide susceptibility maps. The methodology followed in the current work is the comparison and evaluation of the landslide susceptibility that derives from a statistical method (quantitative analysis) and a semi-qualitative expert based method. Along with the landslide inventory, some commonly used predisposing factors such as lithology, land use, slope, distance from road network etc. were selected and included in the procedure. Thus, the Frequency Ratio (FR) statistical model was selected to define weights for each class of each factor.

Results: The process was repeated both in each of the selected regions and in Greek territory, in order to attempt to find any trends of the weights. The Landslide Susceptibility Index (LSI) was used for landslide susceptibility mapping in ArcGIS environment. This index was expressed as an algebraic summary of weights according to bivariate statistical analysis. As a means to checking the reliability of the proposed susceptibility model, Success Rate Curves were also derived. Thus, the landslide susceptibility map that resulted for each different region, classifies the study areas into five landslide susceptibility zones. However, a heuristic approach is considered to be the most appropriate for obtaining landslide susceptibility maps for large areas, especially when lacking sufficient landslide inventories. The results from the statistical analysis of the training areas mentioned above, will be used to develop the final landslide susceptibility map of Greece using an Analytical Hierarchy Process (AHP) method.

Conclusions: While Hellenic Survey of Geology and Mineral Exploration HSGME serves the public and the authorities by providing reliable scientific information and thus minimizing loss of life and property from natural disasters, this research could be a basic tool for managing a sustainable hazard and risk mitigation program in landslide prone areas.

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THE COLLABORATION BETWEEN BIVARIATE AND MULTIVARIATE STATISTICAL METHODS IN DETERMINING LANDSLIDE SUSCEPTIBILITY ZONES IN GARUT REGENCY, WEST JAVA PROVINCE, INDONESIA

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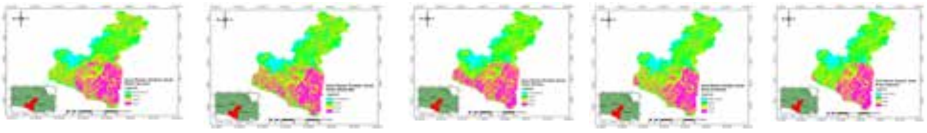
Purpose: Landslides are one of the most frequent natural disasters in Indonesia. Based on BNPB, it was recorded that in 2020, 1152 landslide events spread throughout Indonesia. This research was conducted in Garut Regency, West Java Province. West Java Province is one of the areas vulnerable to landslides, with 407 landslide events in 2020. Based on BNPB, from 2000 to 2020, there were 161 landslide events in Garut Regency. This research aims to determine the monthly landslide susceptibility zones in Garut Regency with the Weight of Evidence (WoE) and Logistic Regression (LR) methods. It also aims to determine which method is more accurate in this research. The landslide susceptibility zones are generated by landslide susceptibility map.

Methods: This study uses two methods to determine landslide susceptibility zones: WoE and LR. WoE methods can evaluate the effect of a class from a parameter on the occurrence of landslide events (Getachew & Meten, 2021). In comparison, LR methods can analyze the correlation of each parameter used in this research. The parameters used in this research are elevation, slope, slope aspect, curvature, NDVI, distance to river, distance to road, distance to lineament, land use, lithology, and rainfall on a monthly basis (Liao et al., 2022). This research uses 104 landslide events data from 2000 to 2020 that are divided into two groups, training set (70%) and test set (30%). The training set was used for the validation model of the success rate (SR), and the test set was used for the predictive rate (PR). Both data sets were calculated using Area Under Curve (AUC) graphic.

Results: Landslide susceptibility Maps using WoE:



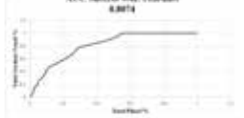
WoE Landslide Susceptibility Maps From January to December

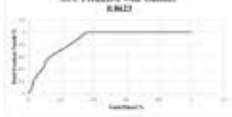
Landslide susceptibility Maps using LR:

LR Landslide Susceptibility Maps From January to December

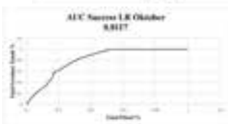
Validation of WoE and LR using AUC Graphic

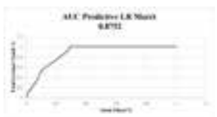
The WoE model has an AUC SR value ranging from 0.76 - 0.80 and PR value 0.81 - 0.86. While the LR model has an AUC SR value ranging from 0.74 - 0.81 and PR value 0.82 - 0.87.





The Highest AUC SR (February) and PR (October) of WoE





The Highest AUC SR (October) and PR (March) of LR

Conclusions: The landslide susceptibility zones are divided into four zones: very low, low, medium and high zone. The AUC SR and PR results show that the WoE method has a higher accuracy at the SR and the LR method has a higher accuracy at the PR. Based on these results, it can be concluded that the two methods can complement each other.

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A NEW MODEL FOR GLOBAL LANDSLIDE SUSCEPTIBILITY ASSESSMENT AND SCENARIO-BASED HAZARD ASSESSMENT

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Purpose: The landslide susceptibility and hazard assessment model presented in the paper is based on the model developed by NGI (Nadim et al., 2013; Jaedicke et al., 2014), but with the improvements and refinements that have been made in various projects since then.

Methods: The basic model was originally developed for the project "Natural disaster hotspots – a global risk report" for the World Bank (Dilley et al., 2005) to identify the global landslide hazard and risk "hotspots". This model was used in the Global Assessment Reports (GAR) of UNDRR and is referred to as the GAR model in this abstract. The scale of the analysis in the GAR model was a grid of roughly 1km × 1km pixels where landslide hazard, defined as the annual probability of occurrence of a potentially destructive landslide event, was estimated through a combination of the triggering factors and susceptibility factors. The model presented in this paper focuses on rainfall-induced landslides. Its resolution is about 10 times greater than the GAR model and it can be used for the assessment of landslide probability for specific rainfall scenarios. In the new model, a susceptibility index is evaluated using the following equation:

$$Sus_{rain} = S_r \cdot S_l \cdot S_h \cdot S_v$$

where Sus_{rain} is the landslide susceptibility index for rainfall-induced landslides, S_r is the slope factor within a selected grid, S_l is lithological (or geological) conditions factor, S_h depends on the absolute amount of annual rainfall at the location of interest, and S_v is the vegetation cover index. The weights of different susceptibility factors were calibrated to the information available in landslide inventories and physical processes. To assess the probability of landslide for a given rainfall scenario, a triggering index Tp is defined based on the return period of the rainfall event for that scenario at the location of interest. The "landslide hazard", i.e., the probability of landslide occurrence for that specific rainfall event, is derived from the combination of susceptibility index and triggering index. These probabilities are calibrated such that the total number of significant annual rainfall-induced landslides in the world is roughly 400,000 (The World Bank, 2020).

Results: The main result is an improved model for scenario-based landslide hazard assessment. The key modifications of the new model compared to the GAR model are:

- The increased resolution on the DEM and consequently the slope data (3 arc-second resolution in the new model compared to 30 in the GAR model).
- The rainfall triggering factor is based on an extreme-value analysis of 1-day precipitation, as opposed to the extreme monthly precipitation in the GAR model.
- The use of most up-to-date inventories for calibration of susceptibility and triggering factors.

Conclusions: The new model is used in the Flagship Report of The Coalition for Disaster Resilient Infrastructure (CDRI) to evaluate the global risk posed by landslides to road and railway infrastructure, both for the present climate regime and for future climate scenarios. The support of CDRI for the development of the new landslide susceptibility and hazard model is gratefully acknowledged.

EVALUATING LANDSLIDE SUSCEPTIBILITY IN NORTHERN PHILIPPINES USING MACHINE LEARNING

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Purpose: Annual rainfall-induced landslides are prevalent in the northern Philippines, owing to its mountainous environment and frequent occurrence of high rainfall events that often exceed 100 mm over a 24-hour period during the rainy season. Landslide susceptibility models, based on rational mathematical methods, are critical for identifying high-risk areas and informing land use and development decisions to mitigate landslide risks and protect local communities. This study evaluates the effectiveness of state-of-the-art machine learning (ML) methods for determining landslide susceptibility in an area in Benguet province.

Methods: A total of 5486 points, including 2567 landslide and 2919 non-landslide points, were randomly selected from maps and field surveys across a 40 square kilometer area. The normalised difference vegetation index (NDVI), land use/land cover, lithology, slope aspect, and slope angle were used as input landslide conditioning factors for machine learning classification models, such as k-nearest neighbours (KNN), random forest (RF), artificial neural networks (ANN), Gaussian process (GP), and support vector (SV), to predict landslide susceptibility (1-landslide, 0-no landslide). The best model was chosen using five-fold cross-validation on 90% of the data, and the remaining 10% was used for validation. The model's accuracy was evaluated based on true positives (TP), true negatives (TN), false positives (FP), and false negatives (FN) using the model's predictions. Accuracy reflects the model's ability to predict points correctly and can be calculated using the formula below.

Results: Figure 1(a) shows the cross-validation accuracy scores of various ML models with optimised hyperparameters. All models perform well, with the GP model showing the highest accuracy of 84.51%. Figure 1(b) presents the confusion matrix of the GP model on the validation set, highlighting the model's effective predictions for both landslide and non-landslide classes. However, the model tends to have more true negatives (non-landslide cases) and slightly fewer true positives (landslide cases), resulting in a higher occurrence of false negatives than false positives. Additional data and model training could improve this.

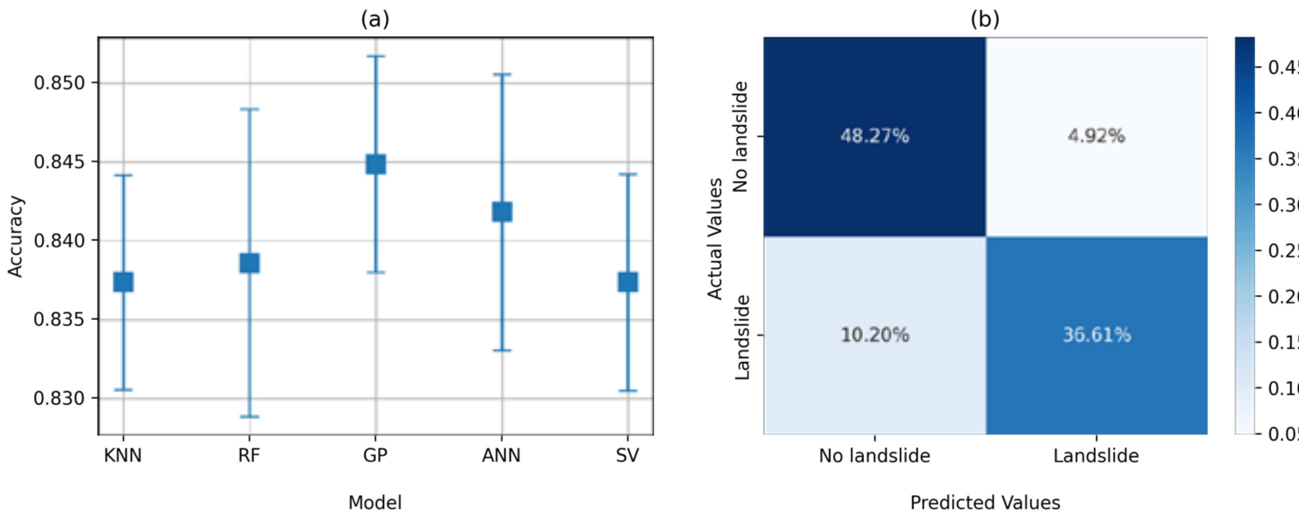

Fig. 1. (a) cross-validation accuracy scores of different ML classification models, (b) confusion matrix of the GP model predictions on the validation set.

Conclusion: This study evaluated ML models in predicting landslide susceptibility in an area in the province of Benguet in northern Philippines. The GP model outperformed other models with an accuracy of 84.51%. While false negatives occurred more frequently, further refinement can address this. This study highlights the potential of ML models in providing accurate landslide susceptibility maps that may guide disaster prevention efforts.

INITIATION AND MOBILITY OF FLOWS IN THE SOUTHERN APENNINES OF ITALY

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Flow-like movements are extremely widespread in the Italian Apennines, and range in size from small earthflows to large landslides that locally cover extensive areas, especially when they are fed by multi-source areas (Parise et al., 2012; Spalluto et al., 2021). This allows an almost continuous contribution of material, typically occurring in connection to, or immediately after, the main meteoric events. Even though generally characterized by slow to very slow velocities, their occurrence is often the cause for serious impacts on society, as for instance experienced in 2010, when the Montaguto earthflow (Lollino et al., 2020) invaded a state road, and soon after reached the railway line connecting the southern Adriatic side of Italy to Rome, creating problems for several months and severe economic losses.

Starting from an extensive dataset of mass movements, recently developed for the Daunia Apennine (western Apulia, southern Italy) within the framework of a regional project dedicated to geohazards (Ardizzone et al., 2023), funded by the Apulian Civil Protection, we analyze in this paper the sub-sample of flow-like phenomena, from a geological as well as geotechnical standpoint, aimed at understanding the combined conditions of geology, morphology and geotechnical properties which are at the origin of different behavior of the flows, in terms of covered areas, length of the flow, and impacts on towns and infrastructures. At this aim, the geological formations cropping out in the area are distinguished in terms of lithology, clay content, grain size distribution, boulder content and hydrogeological and geotechnical features, aimed at identifying the combination of parameters which appear to control the initiation of the phenomena and the corresponding transition from slide to flow-like processes.

Once started, the later evolution of the flows is strongly controlled by water content, availability of further source of water (that is, continuous rainfall or formation of lakes and ponds in the upper landslide sectors), slope gradient, etc. All these parameters are evaluated to understand the difference in mobility and in runout within the considered sample of flow-like movements, thus highlighting those parameters that are recognized as the most relevant to enhance the earthflow mobility.

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TESTING THE EXPLOITABILITY OF HETEROGENEOUS REGIONAL LANDSLIDE INVENTORIES IN SUSCEPTIBILITY ASSESSMENT: AN APPLICATION TO THE VOLCANIC SYSTEM OF EL SALVADOR

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Purpose: Landslide susceptibility mapping through statistical modelling offers a well-consolidated risk mitigation tool, which requires the availability of reliable landslide inventories for model calibration. However, merging heterogeneous inventories for regional mapping can result in well-performing models but hide potential strong predictive deficiencies. In particular, biased or incomplete inventories can significantly hamper the accuracy and reliability of the final maps. In this research, a test has been carried out aimed at suggesting a model building and validation procedure suitable for detecting and investigating this potential source of model inefficiency.

Methods: A set of independent available debris flow/slide archives from five different sectors of the El Salvador territory (Ilopango (ILO), Coatepeque (COA), San Miguel (SMG), San Vicente (SVC), and San Salvador (SSV) areas) were exploited for training and validating a regional landslide susceptibility map. The landslide inventories even in the same sector are affected by heterogeneities in terms of operators, methods (field/remote), and epoch (which means grouping debris flows/slides linked to multiple and/or different extreme rainfalls). Susceptibility mapping was then performed, by applying Multivariate Adaptive Regression Splines (MARS) to regress the outcome (stable/unstable status) on the covariates. First, a grand model (ALL) was prepared by including in the processed data frame the whole set of positives and negatives cases from the five sectors. The ALL model was validated according to both a self-validation scheme (ALL_ALL) and on a local scale by importation into every single sector in turn (e.g., ALL_ILO). For comparison, independent local models (e.g., LOC_ILO) were also prepared to apply a local self-validation scheme.

Results: The performance of the ALL_ALL model is very high, with excellent AUC and accuracy (0.87 and 0.76, respectively) and highly satisfactory sensitivity (0.82) and specificity (0.76). Comparing these values to the ones obtained in importing the grand model into the specific sectors (ALL_local), satisfactory to excellent AUC and ACC values still hold, with the exception of ILO and SSV. At the same time, the locally calibrated models resulted in smoothly (with the exception of SSV) higher AUC values, with a proportional decrease in the cut-off-dependent accuracy, but driven by a marked sensitivity increase and a slight specificity decrease. By comparing ALL_local to local models, it was observed that: lower sensitivity and higher specificity were recorded for all the models, with the exception of ILO. In particular, the greater the landslide incidence of a single sector, the higher the TPR decrease recorded for the imported models.

Conclusions: According to the obtaining results, grouping landslide inventories from different areas to increase the number of cases can lead to unreliable results unless further validation tests are carried out. In particular, depending on both the number of landslides and frequency distribution of all the predictors in each of the grouped sectors, the obtained regional model can produce very high performance on the whole, but resulting in very misleading and unstable prediction images, on a local scale. In light of this effect, locally calibrated models can have better performance even if trained with a lower number of cases.

GIS-BASED EVOLUTION AND COMPARISONS OF LANDSLIDE SUSCEPTIBILITY MAPPING OF CHIANG RAI PROVINCE, NORTHERN THAILAND

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Purpose: Creating accurate and effective landslide susceptibility maps can effectively use for landslide risk reduction measures to reduce people's life and property. Choosing the appropriate modeling factors and method are the key to establish an accurate and practical landslide susceptibility model. The main purpose of this study aims to apply and compare the rationality of landslide susceptibility maps using different causative factors in Chiang Rai Province, Northern Thailand.

Methods: A total of 5,419 landslide points were mapped from Google Earth images and field survey. Two thematic map sets were prepared to examine landslide causative factors. The first set composed geological, morphological and land use conditions including of 1) lithologic units, 2) the distance of structure, 3) elevation, 4) slope, 5) land use, 6) flow direction, and 7) aspect. The second set composed of the variable related only to digital elevation models (DEMs) including 1) curvature, 2) slope, 3) sediment transport index (STI), 4) topographic Position Index (STI), 5) topographic roughness index (TRI), 6) topographic wetness index, and 7) stream power index (SPI). GIS mapping and analysis using a Frequency Ratio Model was implemented in this study to assess the contribution of conditioning factors to landslides, and to produce a landslide susceptibility map of the study area. Landslide susceptibility classified by standard deviation was used to divide landslide levels.

Results: The result showed similar performance. The key parameter of landslide susceptibility mapping in Chiang Rai Province is Slope.

Conclusions: Landslide susceptibility of Chiang Rai Province, Northern Thailand can be created by using the variable related to digital elevation models (DEMs).

SESSION 3.7

ADVANCEMENTS IN LANDSLIDE AND DEBRIS FLOW MITIGATION USING GEOSYNTHETICS AND OTHER SOLUTIONS

ANALYTICAL MODELLING OF THE MECHANICAL BEHAVIOUR OF THE INTERACTION BETWEEN SOIL AND ANCHORED GEOSYNTHETIC SYSTEMS

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Anchored geosynthetic systems (AGSs) are commonly adopted as a technique for both stabilizing potentially unstable slopes [2] [3] and erosion control. AGSs are constituted by geosynthetics and an anchoring system composed of driven rods. The installation involves anchor driving at given spacings through geosynthetics positioned over a slope surface. Vitton et al. [4] observed that AGSs work mainly as a passive system: the geosynthetic tension develops while slope displacements occur, thus stabilizing the slope.

These reinforcement structures are commonly designed according to ultimate limit state approaches or, less frequently, by means of “hybrid methods” [1]. To use the former approach the maximum value of the stabilizing force provided by the retaining structure has to be calculated, while according to the latter the whole relationship between force and far field soil displacement is necessary. Since geosynthetics interact with the underneath soil and behave as a membrane, both materials and geometrical non-linearities play a primary role. Therefore, predicting the stabilizing force can be achieved only by correctly simulating the local soil-structure interaction and by taking into consideration local yielding of both soil and geosynthetic and second order effects. Up to now, the expected interaction force is provided by the producer according to experimental punching test results.

Alternatively, the authors here introduce a meta-model, not requiring neither laboratory punching test nor numerical analysis results, capable of assessing the stabilizing force, once soil-geosynthetic mechanical properties and geometry are assigned. This tool is based on the introduction of the so-called characteristic curve: relationship between far field soil displacements and both retaining force and geosynthetic tensile force. The anchoring plate along with a portion of the surrounding geosynthetic, in which normal stresses develop, are assumed to behave like a sort of “deformable heterogeneous foundation”, progressively increasing in size with far field soil displacement. This concept is introduced in standard load-displacement curves for shallow foundations, by suitably modifying bearing capacity formula.

Such a tool is suitable for being employed by both (i) producers to optimize the use of their products and (ii) designers to reduce the intervention costs and to increase the retaining system sustainability without performing ad hoc finite element numerical analyses or an expensive parametric experimental campaign.

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3D PRINTED REINFORCEMENT FOR SOIL STABILIZATION

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Purpose: Mountainous regions, especially those with steep slopes or problematic soils, are vulnerable to landslides and disasters during heavy rainfall and earthquakes. To address this issue, researchers have explored different remediation schemes, including soil stabilization, reinforcement, anchors, and micro piles (Xiao et al. 2017; Liang et al. 2019; Tao et al. 2019). The aim of this study was to investigate the impact of 3D printed reinforcements on soil reinforcement, considering both 2D and 3D structures. To deepen our understanding of soil reinforcement mechanisms and optimize the potential and design of 3D printed reinforcements, 3D finite element analysis was also conducted.

Methods: In this study, consolidated undrained triaxial tests were conducted on laboratory-grade sand under varying confining pressures (100, 200, and 300 kPa) to evaluate the effectiveness of both 2D and 3D reinforcements. The 3D printed reinforcements were produced using high-toughness thermoplastic elastomer and generated with drawing software. These reinforcements were then placed horizontally in the center of 5 cm diameter and 10 cm height specimens. Furthermore, the mechanical behavior of reinforced soil was simulated by a 3D finite element analysis, with the goal of evaluating the effectiveness of 3D printed reinforcements in enhancing soil behavior.

Results: The stress-strain curves demonstrate that reinforcements effectively restrain soil deformation and delay failure. The use of 2D reinforcement caused barrel-shaped deformation only at the upper part of the soil, while 3D reinforcement resulted in smaller deformations at both the upper and lower parts, indicating a greater effectiveness in restraining soil deformation. The lateral binding force and higher vertical reinforced elements in the 3D material effectively enhanced shear strength. Furthermore, 3D finite element analysis can reasonably simulate soil behavior with reinforcement, providing a valuable tool for further understanding the efficacy of reinforcements in restraining soil deformation and delaying failure.

Conclusions: The study results demonstrate that 3D printed reinforcements have the potential to increase the shear strength of soils. The inclusion of both 2D and 3D reinforcements was found to significantly improve the strength of the soil due to the lateral binding force created by the reinforcements that helps to prevent direct shear failure. The validity of the experimental results is further supported by the 3D finite element analysis. Nevertheless, further investigations are needed to gain a better understanding of the reinforcement mechanisms and accurately assess their efficacy under various conditions.

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Keywords: reinforcement, triaxial test, finite element analysis, 3D printing, soil stabilization

GREEN PROTECTION BARRIERS AGAINST DEBRIS AVALANCHES

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The analysis of the Landslide-Structure Interaction (LSI) is a difficult yet crucial task, especially in the case of a flow-like landslide impacting a protection barrier. In fact, while researchers have used several approaches, from experimental to numerical, it is true that the adequate assessment of the hydro-mechanical behaviour of the landslide body requires both a multiphase and large deformation approach. In fact, the evaluation of the impact forces on mitigation obstacles remains difficult especially if the solid-fluid interaction within the flow is considered. In addition, flow-like landslides are often characterized by large deformations, which depend on slope geometry, soil type and triggering mechanisms.

The first fundamental step is the landslide triggering and propagation analysis in the mountain catchment. The propagation analysis gives insights about landslide volume, velocity, thickness, shape and length before the impact against an obstacle. Therefore, LSI can be studied focusing the attention on the moment before the impact, considering a simplified initial configuration of the landslide as input (a single landslide or a set of landslides). In this study, a landslide with a steep front and a prolonged tail is the input of the numerical analyses, also considering different landslide volumes. Once given velocity, thickness, unit weight, length, shape and volume, the literature empirical methods can be easily used to estimate the peak pressure (or force) expected at the impact against the barrier.

Based on that, three analysis approaches are presented and applied to different landslide geometries. The approach no.1 (empirical) allows estimating the impact force and the flow kinetic energy release over time. The approach no.2 (analytical) also provides the displacement of the barrier due to the impact. The approach no.3 (numerical) fully simulates the Landslide-Structure-Interaction (LSI) also including the estimate of the amount of landslide volume overtopping the barrier. An advanced numerical code based on Material Point Method (MPM), i.e., the Anura 3D code (and related developments done by Deltares) is used thanks to its capability of considering both the coupled hydro-mechanical behaviour and the large deformations of the propagating mass. The required input parameters and the achievable results through the three approaches are illustrated and compared.

The study shows that the distinct methods are generally in good agreement, because they are all adequate to reproduce the physical processes of the LSI. The combined use of multiple methods is fully encouraged to provide a range of solutions for the design protection barriers.

HOW EFFECTIVE WAS SLUICING AS A ROCKFALL REMEDIATION METHOD FOLLOWING THE 2016 KAIKOURA EARTHQUAKE?

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Coseismic landslides during the 2016 Kaikōura, NZ, earthquake significantly affected road and rail infrastructure resulting in the isolation of communities and requiring urgent remediation to restore a nationally strategic transport link. In the initial response, large-scale helicopter sluicing was used to remove loose debris from earthquake-damaged slopes. Heli-sluicing is a novel and uncommon approach to landslide mitigation globally, but was used extensively post-earthquake, with up to 220 million litres of seawater dropped on more than 40 coastal landslides. Despite its widespread use in the earthquake response, little has been published on the approach, effectiveness, and cost-benefit of heli-sluicing coseismic landslides. In particular, comparing the effect of natural rainfall on post-earthquake source zones compared to targeted sluicing operations. The Kaikōura earthquake presented a unique case study to test these questions, as a series of ex-tropical cyclones passed over the area damaged by the fault rupture in the years following the event. {Justice

The effectiveness and cost-benefit of heli-sluicing relative to natural rainfall was investigated using a combination of helicopter flight path data, time-series rockfall data, and the National Institute of Water and Atmospheric Research (NIWA) High-Intensity Rainfall Design System (HIRDS) database. This data was supplemented with field investigations and ground truthing within the study area. The data was first used to identify which slopes were heli-sluiced, with the landslide lithologies, failure types and volumes determined. Two sample groups within the rockfall dataset were created: i) rockfall generated from sluiced slopes, and ii) rockfall from slopes left to natural rainfall. Temporal rockfall rates in each sample group were examined to determine if a relationship could be drawn between faster slope 'recovery' i.e., reduced rockfall hazard over time, and sluicing. NIWA's HIRDS rainfall data were used to compare the behaviour of the two sample groups under periods of high-intensity rainfall.

Landslides subjected to heli-sluicing show a marked decrease in post-seismic rockfall rates compared to non-sluiced slope failures, which continue to produce heightened rockfall activity. Nevertheless, many of the slopes that were sluiced also had rockfall protection structures installed to stop post-seismic rockfall reaching the road, with no major differences in the rates of rockfalls reaching the highway observed between sluiced and non-sluiced slopes. While sluicing tended to accelerate slope recovery to the point of acceptably reducing rockfall hazard for specific lithologies and landslide failure mechanisms, rockfall protection measures appear to have equally reduced the risk, albeit not the rate of rockfall. Consequently, the cost of many of these permanent rockfall protection structures on sluiced slopes, with their associated installation and maintenance costs, will soon exceed the benefit as the hazard they were installed to protect against was meaningfully reduced through sluicing operations. Whether the initial cost of heli-sluicing is sufficient to offset the reduced duration of maintenance costs remains contentious. Sluicing is generally accepted as having played an important role in accelerating slope 'recovery', with this study presenting the first quantitative test of its performance post-earthquake.

APPLICATION OF TWO-DIMENSIONAL SHALLOW WATER EQUATIONS IN DEBRIS FLOW MODELLING: A CASE STUDY IN MARUMORI, MIYAGI, JAPAN

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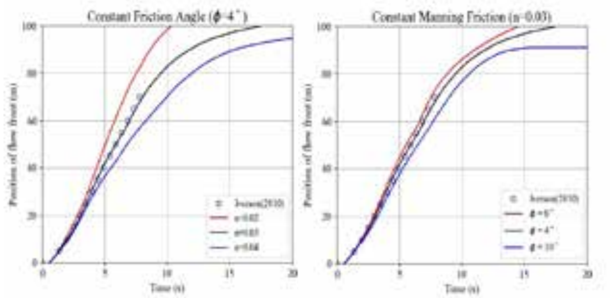
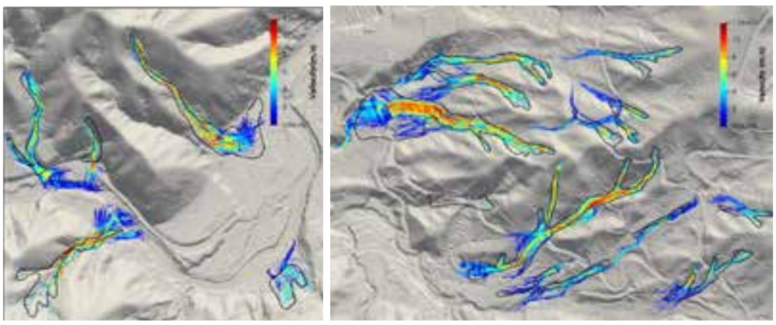
Purpose: Debris flows are a common natural geohazard that causes significant damage in mountainous regions. Commonly triggered by earthquakes or rainfall, debris flows often travel over long distances in a fluid-like manner causing destruction along their path. While the prevention of debris flows remains to be challenging, numerical simulation and modelling are useful in minimizing the damages inflicted on the affected communities. Therefore, this study employs a smoothed particle hydrodynamics (SPH) approach in discretizing the two-dimensional shallow water equations (2D SWE) to better understand the post-failure behavior, propagation, and extent of multiple debris flows over a wide area.

Methods: To facilitate practical computations over wide areas, the debris flow is considered as a single-phase homogenous viscous fluid governed by the depth-integrated 2D SWE. Rheological modelling is applied by modifying the equation's flow resistance terms and parameters. Particularly, this study employs the Manning's and Coulomb's flow resistance relationships. The parameters are then calibrated using intuitive conditions, laboratory experiments, and past events. The governing equations are discretized into soil particles or columns using the mesh-free Lagrangian SPH approach. The models are applied to the debris flow flume experiments of Iverson et al. (2010); and the actual debris flows disasters that occurred in Marumori, Miyagi, Japan.

Results: After some parameter fitting and calibration, the model was shown to agree well with the experimental results. The parameters that best replicated the experimental results were shown to be Manning's friction coefficient n=0.03 and internal friction angle ϕ=4o.



The n-coefficient value corresponds to rough concrete or gravel channels consistent with the conditions of the experimental setup, while the friction angle translates to the residual strength of a fluidized post-failure mixture of soil and water. The model was then applied to simulate the debris flow disasters that occurred in Marumori, Miyagi, Japan using the calibrated parameters. The Manning's friction coefficient, however, was modified to correspond to mountain streams lined with cobbles and boulders (n=0.07). The simulation results were shown to agree with the delineated damaged areas.



Conclusions: Using an SPH-based approach in solving the depth-integrated shallow water equations, the propagation velocity, behavior, and extent of an idealized single-phase debris flow can be modeled. Calibration of two material parameters related to the flow resistance terms allows the model to conform with past or experimental data. Despite the numerical and theoretical simplifications, this study was shown to successfully reproduce the flow velocities of the experiment of Iverson et al. (2010) and the runout extent of the debris flow disasters that occurred in Japan. Therefore, given proper calibration, the model can be used in the evaluation, assessment, or mitigation of would-be future debris flow hazards in the area. Moreover, the simplified two-dimensional framework provides a practical alternative for wide-area studies.

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EXPERIMENTAL INVESTIGATION OF NEGATIVE POSSION'S RATIO STRUCTURES TO ARREST GEOPHYSICAL GRANULAR FLOWS

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Purpose: Designing flexible barriers that can regulate discharge through it while reducing the peak impact load remains an engineering challenge. Conventionally, a flexible barrier net, which is made with positive Poisson's ratio materials, elongates in the longitudinal direction by tension and contracts in the transverse direction when it is impacted. In turn, this reduces the porous area of the net and then the debris is trapped behind the barrier. In contrast, negative Poisson's ratio material can stretch in both the transverse and longitudinal directions upon impact, increasing the porous area for debris to pass through the net. Negative Poisson's ratio nets appear to be a promising technology to be adopted to progress towards self-cleaning flexible barriers. In this study, we propose to develop a self-cleaning barrier net by using negative Poisson's ratio structures. More specifically, 3D printing is used to manufacture flexible barriers consisting of unit cells of negative Poisson's ratio auxetic structures (NPRAS).

Methods: To evaluate the performance of adopting NPRS flexible nets for arresting granular geophysical flows, a new vertical chute experimental setup is developed. The setup consists of a net affixed to an instrumented frame to measure the impact force exerted by a free-falling granular mass in a chute using load cells. The granular mass is initially retained by a trap door. High speed cameras are used to capture the impact kinematics and to measure the deformation of the net. Video camera are used to record the whole process of impacting and discharging. Two mainstream NPRS, specifically the re-entrant hexagon and the double-arrow shape structures, are tested. In addition, the performance of non-NPRS nets and rigid barriers are compared with the performance of the NPRS nets.

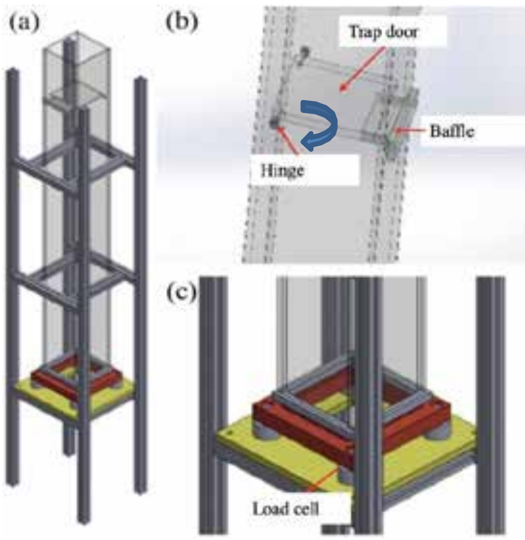

Fig. 1. Schematic of the experimental setup. a. Overview of the vertical chute; b. Schematic showing the working principle of the trap door; c. Enlarged view of the frame for mounting the net.

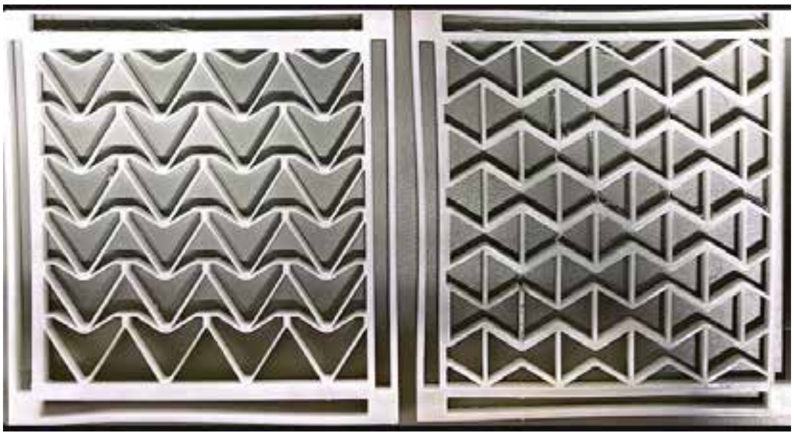

Fig. 2. Two types of NPR net manufactured by 3d printer. The net on the left consists of re-entrant structures, the net on the right consists of double-arrow structures

Results: The net with openings reduces the peak force by 9% compared to acrylic sheet; the net made with softer material reduces the impact force by 30%. Compared to the re-entrant hexagon, the double-arrow shape NPRS has more significant NPR deformation characteristic, a lower probability of clogging. Preliminary results show that the NPRS nets not only attenuate the impact force by up to 27% compared to non NPRS nets but can also entirely prevent clogging if it can be fully deformed during the impact.

Conclusions: Both the stiffness of the barrier and the discharging of granules will attenuate the impact force, but the former factor plays a dominant role. Compared to conventional structures, the NPR structure can significantly attenuate the impact force and discharge granules with less clogging possibility. Well-designed NPR structure have the potential to be self-cleaning materials for mitigating geophysical granular flows

EVALUATION OF SLOPE PROTECTION WORKS FROM SHEAR STRAIN IN GROUND WITH SOIL NAILING BY CENTRIFUGE TESTS

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Purpose: There are many kinds of slope protection works for soil nailing method (shown in Figure 1) in Japan. The slope stability of a steeply inclined slope is a key issue for which soil nailing is commonly adopted as a countermeasure for the disaster resilient slope designing. However, there are no appropriately established procedures so to acquire the maximum countermeasure against slope failure. Slope loading experiments with geotechnical centrifuge facility were conducted for the purpose of research to understand the effectiveness of the slope protection works and evaluated by maximum shear strain.

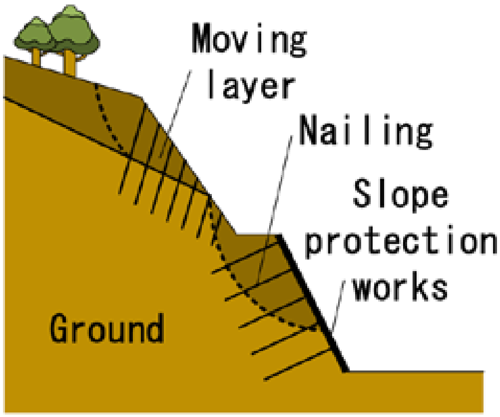

Fig. 1: Soil naling.

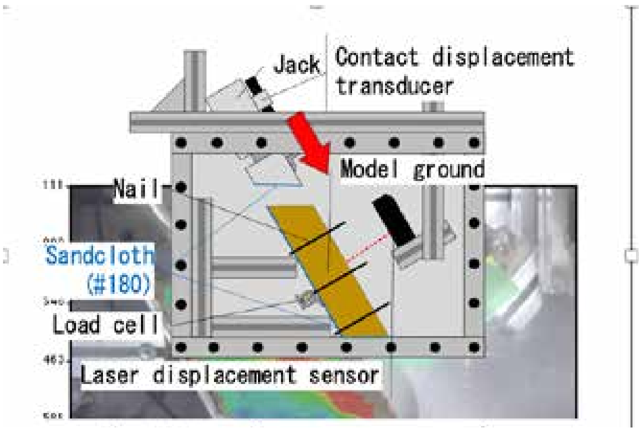

Fig. 2: Experiment summary chart.

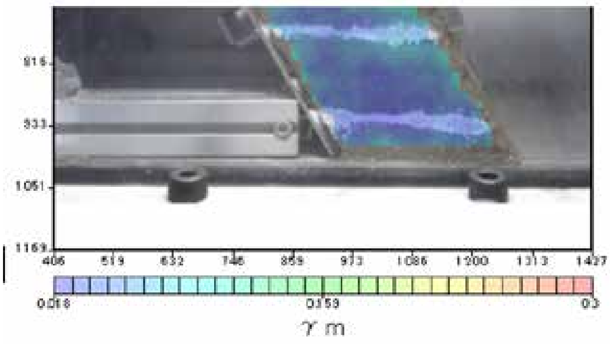

Fig. 3: Image analysis result (Shotcrete)

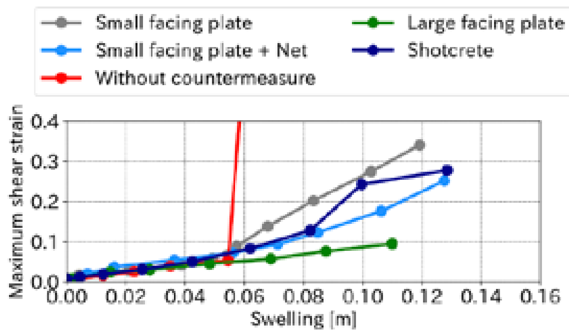

Fig. 4: Relationship between swelling and maximum shear strain

Methods: Slope loading experiments were conducted using a geotechnical centrifuge facility (TCU Mark II Centrifuge) owned by the Tokyo City University. Soil used in this research was a mixture of Ao clay and silica sand No. 7 with a dry weight ratio of 1:3 and a water content of 13%. The model ground was divided into four layers and was compacted from the sides to achieve a wet density of 1.78 g/cm3 (degree of compaction, Dc = 88%). All experiments were conducted at a centrifugal acceleration of 40G. The load was applied in-flight with a magnitude of 9.2 kPa for every 2 minutes interval using an air jack placed at the top of slope surface. The displacement of the jack and the swelling magnitude at the midsection of slope was recorded using a contact displacement transducer and a laser displacement sensor respectively. For the experiments with soil nailing, the nail was inserted from the slope face into an attached small size load cell to measure the tensile stresses acting on the nail (shown in Figure 2). A following series of experiments were conducted: (a) without countermeasures (b) small/large facing plates and (c) small facing plates with the nets. Pressure gauges were placed above and below the facing plate at the center of the slope to measure the pressure acting on the plate. Additional experiment with a model shotcrete were also performed for comparison.

Results: Figure 3 shows a typical example of maximum shear strain, γm for the test with a model shotcrete. In the figure, γm increases accordingly as the color changes from blue to red. Figure 4 shows the relationship between swelling at the midsection of the model slope and γm. From the Figure, one can observe a sudden slope failure with a significant rise in maximum shear strain when without countermeasure was used as compared to the other cases. The countermeasure involving a large facing plate was found out to be the best remedial measure.

Conclusions: In this study, different countermeasures against slope failure were examined and design recommendations were made for the disaster resilient design of slopes based on geotechnical centrifuge modeling.

RISKS ASSOCIATED WITH THE MANAGEMENT OF STRUCTURAL PROTECTIVE MEASURES FOR ROCKFALL MITIGATION: AN OVERVIEW ON THEIR SUPERVISION AND MONITORING OVER TIME

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Purpose: Rockfalls are extremely widespread events in mountainous areas worldwide, representing a major hazard that causes considerable damage and victims. In Italy, over the past decades, considering the safety of road network and settlements, remarkable impulse was given to the installation of rockfall barriers and other mitigation strategies. Implementing structural protective measures for rockfall mitigation has led to installing various protective structures (e.g., nets, barriers, embankments). These structures may vary considerably depending on age of construction or design, showing a progressive development due to the regulation governing design, construction and maintenance. Hovewer, for most of this vast number of structural protective measures their georeferenced location, their maintenance and the possible changes that occurred to the surrounding slope are unknown data, thus representing a crucial issue in mountainous territories.

Methods: Commonly, in highly landslides prone areas, detailed inventories of the occurred events are implemented by regional administrations, leveraging on dedicated geodatabase, and providing constant updating over time. For a proper rockfall risk management, administrations such as the Aosta Valley Region provide for not only a detailed inventory of the occurred phenomena, but also the implementation of remedial actions and works to reduce the risk level, with a regionally systematized procedure. Also, at local scale, as in the Lauria municipality (Basilicata Region), noteworthy procedure for managing and monitor the state of the structures as well as of the as the slope, through a geocoding of mitigation works, has been implemented. New generation of smart network were also tested in some alpine areas in Piemonte and Aosta Valley regions in order to monitor both risk mitigation structures and rock masses (LASMON Project), allowing to control the effectiveness of these structures and their partial or total damaging by rockfall.

Results: Cases such as these highlighted the need for a comprehensive analysis to properly record the number of the occurred events, define their effect, define the most susceptible areas, plan and maintain the recovery project and suitable remedial works by local and regional administrators. Certainly, the large number of structures and their great variability poses a challenge to define a clear overall framework of all existing rockfall mitigation structures together with their efficiency over time. A systematic study of the efficiency of existing works becomes fundamental for an appropriate management and maintenance of these protective measures.

Conclusions: In this work we proposed a standard methodology to be applied in both local and regional contexts, consisting in diverse phases: i. inventory of the existing structures through the implementation of a geodatabase; ii. definition of a procedure aimed at inspection and maintenance of structures also based on technologically advanced system; iii. development of new generation of monitoring system able to remotely recognize the effect due to rockfall impact able to reduce the operability of protective structures. The proposed system may represent a useful instrument to monitor and plan the maintenance of the rockfall barriers, providing an effective tool for regional and local administrations of mountain areas in risk assessment and mitigation.

PREDICTIVE MODELLING OF DEBRIS FLOW ENTRAINMENT IN CONTRASTING ENVIRONMENTAL SETTINGS

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Debris flows are massively erosive mass movements that pose an increasing threat to infrastructure and settlements in mountainous areas. Effective erosion is a major contributor to the magnitude and hence the hazard potential of debris flows, but it is yet to be sufficiently implemented in models to achieve a predictive performance. We developed a simple predictive erosive debris-flow model, which was calibrated on several active channels in the northern Bavarian Alps. The debris-flows at the study sites recently occurred in 2015 and in 2021, and all entrained more than 80% of their final volume from the sediment channel bed. We calculated the geomorphic changes by comparing pre- and post-event LiDAR data and divided the channels into equal segments and corresponding cross sections. By correlating the modelled flow parameters for each cross section with the eroded volume of the adjacent section, we were able to obtain a correlation that can be used in a predictive debris-flow model to iteratively calculate the erosion. This model allows improved predictions of the magnitude of debris-flow prone channels through a forward-modelling approach.

SESSION 6.1

ADVANCES IN UNDERSTANDING AND MODELLING THE INTERNAL AND SURFACE DEFORMATION OF LANDSLIDES (part II)

SMALL-SCALE LANDSLIDE MODELLING: LIMITATIONS AND CHALLENGES

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Purpose: Physical modelling of landslides is for long time one of the common methods for landslide behavior investigation. After initial experiences with field and laboratory research, the small-scale landslide modelling has found a wide application around the world in different aspects of landslide investigations, analyzing different types of landslides (e.g., flows, slides, falls and toppling) as well as different types of materials (rock mass, sandy, silty and clayey materials) and landslide movements. Although the small-scale landslide physical models, modern monitoring techniques and different sensors and monitoring equipment enable good insight into initiation and development of small-scale landslide models, the main issue is to establish relationship between small-scale, brief, idealized and by artificial boundary restricted model with the complex natural landslide process (Iverson, 2015). Similarity laws that are used to establish these relationships are complex and are consisting of many elements those are interdependent and interconnected.

Methods: The series of small-scale landslide models built of different materials (sand and sand-kaolin mixtures) under different inclinations of slope were exposed to different triggering factors (artificial rain, earthquake at the shaking table) (Arbanas et al, 2022). Landslide initiations and development were observed by complex sophisticated monitoring system (Pajalić et al., 2021; Peranić et al. 2022) that enabled reconstruction of landslide mechanism through overall sliding process in a model. To understand the possibility of landslide remediation, several types of remedial construction were also involved in the model. Measurement results obtained by applied monitoring system enabled establishment of different numerical models for better understanding of overall landslide process.

Results: Measurement results obtained by applied monitoring system at the small-scale landslide models and results of numerical modelling enabled detailed explanation of observed landslide processes in small-scale models. However, attempt of results application to the real slopes and landslides using similarity laws, pointed on complex relationships those should be there at considered. A landslide is a complex geomorphological process, if considering all the factors that should be taken into account when modelling a real landslide, it is clear that a landslide process is too complex for all elements to be covered by the similarity laws to fully describe the mechanism, initiation and run off process of a landslide. The simulation of a real landslide in a small-scale landslide model was limited to the application of the most principal elements affecting a landslide process, while all other elements were adjusted to imitate a real process of sliding.

Conclusions: Although landslide physical modelling is today one of the most significant research method, application of research results from the small-scale landslide models to the real slopes becomes too complex to enable simple switching of results on a large scale. Limitations are caused by interdependent and interconnected elements of similarity laws therefore, the application of numerous research results to real slopes is very rare. At the same time, challenges lie in the development of simplified small-scale models which results can be applied back to the natural modelled slope.

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THE TRIGGERING OF FLOW LIQUEFACTION IN LOESS FLOWSLIDES: A CONSTITUTIVE INVESTIGATION

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Loess can rapidly transform from a cemented solid structure to a fluidized material under wetting-induced decementation. Such a meta-structure can exhibit brittle and intense strain-softening behaviours under undrained shearing, which rapidly reduces shear resistance as yielding is initiated (i.e., flow liquefaction). Retrogressive loess flowslides in the Heifangtai (HFT) terrace in the loess plateau of China with rapid movement and long-runout showing liquefied and fluidized flow responses have been widely reported. The recent NorSand deformation analyses for the HFT loess flowslides showed that the initial failure under a drained condition prior to the subsequent undrained flow failure can result in the triggering condition of flow liquefaction by permitting lateral unloading (i.e., debuttressing) (Zheng et al. 2022). However, the contribution of this lateral unloading has not been studied, and its effects on the triggering mechanism remain unclear. In this study, a constitutive investigation using the Clay-Sand Unified Hardening (CSUH) model is conducted to understand the triggering mechanism of the DC#2 loess flowslide on the HFT terrace. This model is calibrated and validated using the undrained shear response of the HFT silty loess by Liu et al. (2019), and it explores the effects of the changes of the effective principal stresses (i.e., σ'1, σ'2, and σ'3) at the onset of the flow failure through the intermediate stress parameter, b = (σ'2 – σ'3)/(σ'1 – σ'3) The results showed that the increase of the b parameter led to the bending of the critical state line (CSL) of the HFT silty loess at low-confining stress (p' < ~300 kPa), approaching the e0 corresponds to that of a typical triaxial extension test. Such an observation implies that changes in the stress state induced by the initial drained failure led to the favourable condition to trigger flow liquefaction. The model quantifies the interplays of principal stresses on the evolution of the shape and location of the CSLs, and thus, the flow liquefaction susceptibility. A comparative study between the intact and reconstituted silty loess further confirms that the effect of structure promoted the onset of flow liquefaction at low-confining stress.

UNDERSTANDING THE EVOLUTION OF LARGE-SCALE DEFORMATION PROCESSES THROUGH BACK-ANALYSES: KNOWLEDGE ELEMENTS FROM MONITORING AND INTEGRATION OF STRESS-STRAIN AND LANDSCAPE EVOLUTION MODELLING

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Purpose: Back-analysis and reconstruction of factors controlling large-scale slope instabilities is a challenging target for engineering-geologist and geomorphologists, since the knowledge of timing or involved volumes is often fragmentary.

While modelling approaches increasingly accounted for customized constitutive behavior implementing it within numerical solvers, less importance has been given to the morphological reconstruction of the slope asset and the morpho-evolutionary timing of deformative stages. In this study, case studies of slope deformation differing one each other for timing and degree of knowledge are analyzed to collect mosaic tiles drawing evolutionary processes of the slope deformation from primary to ultimate stages.

Methods: In this study ongoing slope deformation processes were approached by a combination of multitemporal digital terrain model acquisitions, in-depth geotechnical monitoring based on triaxial extensometers and instrumented sections made up of radial boreholes instrumented with modular differential accelerometric devices, were adopted to identify sectors of advanced deformation. Results were compared with multitemporal image analysis results carried out with Change Detection and Digital Image Correlation Techniques and collected by LIDAR acquisitions. On the site a preliminary stress strain numerical model was calibrated accounting for different hydraulic gradients within the slope. In case of already occurred, rock avalanches representing tertiary paroxysmal evolution of time-dependent processes, back-analysis approaches encompassing geomorphological markers collections aimed at relative dating, engineering-geological and stress-strain numerical modelling was adopted. Additionally, approaches implementing combinations of 3D landscape evolution modelling (LEM) and 2D stress-strain numerical modelling (FDM) was tested to account for the morpho-evolution of mountain fronts better depicting the geomorphological arrangement where slope deformation process starts, as well as consider inherited regional stress field imposed by tectonics.

Results: The obtained results allowed the addition of elements in the complex framework that regulates slope-scale instabilities featured by a large time- and spatial- span. The monitoring of the ongoing process highlighted localized deformations within the slope caused by a rock mass spreading and driven by karstic degradation, largely confirmed by diagnostic morphological features and geotechnical monitoring within the slope. The latter framed the slope kinematics and the strain rates. Stress-strain modelling also confirmed the role of groundwater circulation in dictating the time progression of deformations. For past rock slope instabilities, modelling allowed reconstruction of the progressive evolution of shear zone driving mass rock creep processes and reproducing the occurrence of slope failure based on volumetric and temporal constraints. The LEM-FDM modelling cascades proved adequate for pre-failure morpho-evolutionary reconstruction and revealed suitable for calibrating the models by back-analysis, constraining temporal range in which processes originated and when critical conditions were reached.

Conclusions: Back analysis can be managed through various approaches that must be selected according to data availability and evolution period. The presented cases reported numerical solutions adopted for reconstructing slope evolution over time, framing factors and mechanisms controlling slope failures. In this sense, the combination of landscape and strain models with slope monitoring will play a key role in advancing the understanding of internal and surface slope behavior aimed at the generation of digital twins devoted to the predictions of future scenarios.

A SMART INCLINOMETER FOR MONITORING THE INTERNAL DEFORMATION OF DEEP-SEATED LANDSLIDES

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Purpose: Very high landslide risks, related to complex phenomenologies involving both towns and strategic infrastructures, characterise numerous areas in the Southern Apennines in Italy. Understanding the landslide kinematics and monitoring its evolution is necessary to manage these risks, in order to keep people safe and to reduce the associated economic impacts. This is extremely important to reduce underinvestment that still affects these areas, which may – otherwise – be involved in Special Economic Zones able to attract both Domestic and Foreing Direct Investments to increase investments, employment, job creation, trade balance and, hence, many goals and targets of the 2030 Agenda for Sustainable Development. In presence of complex gravity-driven processes, inclinometer data remains one of the most useful information although it is characterized by low spatial resolution, and it's a manual time-consuming activity. To overcome these limits, a New Smart Hybrid Transducer (NSHT), an innovative, distributed strain transducer, based on optical fiber sensing technology, has been developed (Minutolo et al., 2020) and its feasibility as smart inclinometer has been tested.

Methods: Two smart inclinometers were installed in the study area of the San Nicola village, near the Cilento coast, to test the effectiveness of the new device to in-depth investigate the landslide mechanics. In the area, an active landslide system (Valiante et al., 2021) involves a superficial layer of landslide debris and a conglomeratic formation which extensively outcrops above the marl-clayey Mesozoic formation. The smart inclinometers were realized by disposing respectively two and four NSHTs along the outer surface of inclinometer tubes 40m long, so that traditional measurements can be performed in the meantime. The adopted sensing technique is based on the Brillouin scattering phenomena which allows detecting the changes of strain and temperature along the NSHT with a spatial resolution of 20cm and a sampling of 19 points/m.

Results: Strain profiles retrieved by the smart inclinometers were consistent with inclinometer data revealing the main features of the slope movement. It also added information not always recognizable by conventional inclinometer monitoring as it reveals not only the horizontal component of the soil deformation, but also the vertical one. During winter 2021 a recorded constant strain profile indicated that the tube was subject to shortening and, hence, that it was suspended inside the landslide body. Indeed, the cumulative displacement profiles retrieved by conventional inclinometer, representative of an earthflow, did not given evidence of a sliding surface. During winter 2022 the smart inclinometer recorded increasing strain changes at three depths in the shallowest part of the conglomeratic formation, revealing the early formation of shallow sliding surfaces.

Conclusions: The measures of more than one year show the feasibility of the NSHT in realizing a stand-alone smart inclinometer, demonstrating the advantage of near-distributed strain sensing over conventional displacement measuring techniques in accurate and long-term monitoring of subsurface deformation for complex landslides.

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USING UAV TIME SERIES TO ESTIMATE LANDSLIDE'S SURFACE DEFORMATION UNCERTAINTIES. CASE STUDY: CHIRLESTI EARTHFLOW, ROMANIA

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Purpose: The current study focuses on assessing the uncertainties associated with the space-time misalignment between the DEMs obtained from UAVs aerial imagery when landslide surface deformations are mapped and evaluated. The case study is Chirlești earthflow, located in the Bent Carpathians, Romania, for which four flights have been flown from 2018 to 2022. This landslide is relatively recent, with significant reactivations in the last decades, which induces a high risk of blocking the DN10 national road that connects the cities of Buzau and Brasov, the main access road for that area.

Methods: The method uses aerial images collected with UAVs (Unmanned Aerial Vehicles) and their derived products obtained from the moving structure technique, but it can be reproduced for any digital elevation models obtained with other means of collection. The landslide volume displacement has been assessed by multiplying the difference in height between two DEMs (MDoD) with the area of one pixel, where MDoD is the DEM of Difference between two dates, t1 is the latest date, and t0 is the earliest date. The changes in landslide surface and volume were assessed by pairing two consecutive flights. A conceptual uncertainty model was developed to account for all these scenarios with possible misalignments between DEMs. The model uses the RMS values of all three axes (X, Y and Z) returned by the orthorectification process and applies random shifts on the X and Y axes to simulate various accuracy values for each DEM. These 360-degree random shifts automatically induce changes on the Z-axis. Because the uncertainty propagation was based on simulations of the RMS values that led to misalignments at the pixel level, a correlation coefficient was used to estimate the degree of misalignment between each pair of flights. This approach allowed having an objective estimate of how RMS values influence the true earth volume displaced during a period.

Results: Four flights were made between 2018 and 2022 using the same drone, DJI Phantom 4, and the same flight plan. Since the area is relatively forested and difficult to access on foot, with reduced GPS signal in the narrow transport sectors of the earthflow, it was preferred to collect the ground control and validation points on the orthoimage and digital elevation model obtained by processing the images collected during the flight made in 2018. Thus all other flights were aligned to this reference. In order to model the propagation of the uncertainties induced by the X, Y and Z RMS values, Monte Carlo simulations were used with different ranges of values. Following the simulations and the analysis, it was observed that an RMS value of a maximum of 1 unit corresponds to a correlation coefficient of at least 0.95 between two successive DEMs. Thus, the RMS value of a maximum of 1 unit can be considered the maximum error allowed for estimating the volume displaced by a landslide.

Conclusions: Using RMS values to simulate the propagation of uncertainties in the DEM made it possible to identify the correlation threshold of 0.95, beyond which any analysis for landslide kinematics assessment becomes unusable. The 0.95 correlation coefficient corresponds to an RMS value of up to 1 unit.

NUMERICAL MODELLING APPLIED TO LARGE LANDSLIDES PHENOMENA

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Purpose: The modelling of large landslides, that involving large volumes of rock, is certainly among the most interesting topics to be addressed due to the need to provide an adequate interpretation of the phenomena in progress. The greatest difficulty lies in the reconstructing of all the elements that contribute to the evolution of the triggering and propagation mechanisms. On these phenomena, the faithful reconstruction of the geological model is not sufficient since the variability of the physical-mechanical characteristics which vary over time and in space assume a decisive importance. Referring to phenomena such as Deep Gravitational Slope Deformation (DGSD), the differences in the rock competence between formations with different ductility assume fundamental importance. In these contexts, the analysis of the states of deformation for high regimes of applied stresses is remarkable, which implies the definition and application of complex rheological models of the Bingham type, for example (viscous elastic-plastic medium). However, DGSDs can locally induce rapid landslides at smaller spatial scales, the evolutionary mechanism of which is connected to the regime of meteoric precipitation and to the geo-hydrological susceptibility of the soils. Therefore, in these cases, the usual numerical techniques are still applied.

Methods: The numerical solution of the common mathematical models entails the discretization of the continuum by grids. The physical quantities of interest (tension, displacements, etc.) are calculated in the resulting nodes. The most common approaches are the Finite-Element-Method (FEM), or the Finite-Difference-Method (FDM). As an alternative there are "mesh-less" methods, such as Smoothed-Particle-Hydrodynamics (SPH). Another element is how to be able to represent the variability of the physical-mechanical parameters in the space. In general, within the soils, zones are located with diversified structural characteristics are randomly distributed within layers or around planes or curved lines. It is therefore necessary to provide for a multiscale characterization of the heterogeneities using algorithms that allow the definition of zone models (macroscopic heterogeneities such as layers and lenses) and/or localized zone models (zones of small thickness relating to planes or bands of weakness).

Results: By repeating the operation, with different possible configurations, different results, and forecasts of the phenomenon evolution under examination are obtained. The processing could require a considerable effort of memory and CPU_time. Therefore, to overcome this difficulty, parallel computing techniques have been proposed and implemented, also on desktops or laptops (Graphical-Processing-Units, GPU, High-Performance-Computing HPC; etc.).To this purpose, a statistical distribution of the numerical values of geotechnical and hydrological parameters, assigned to each node, particle, or element, is assumed. An effective technique is through the pseudo-random-numbers generated by the commonly utilized programming languages.

Conclusions: Moreover, in order to somehow represent gravitational phenomena connected to those types of landslides that are similar to phenomena present in the geological contexts of El Salvador, the landslides of Borrano (in the province of Teramo – central Italy), Marderello test case (in the province of Tourin – North Italy), as representative of Debris Flow and both Roccamontepiano and Lettomanoppello test cases, as examples of Monte Carlo, will be analysed.

NEW TECHNIQUES TO MONITOR LANDSLIDE BEHAVIOR USING DIGITAL TERRAIN MODELS AND IN-SITU GNSS

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Purpose: Landslide hazards pose immense challenges to modern infrastructure. Developing, maintaining, and performing risk assessments of infrastructure on, or close to, hazardous terrain requires a detailed understanding of the geophysical processes destabilizing the slope. These efforts start with the collection of high-quality monitoring data to assess the current rates of slope deformation. Improvements in initial processing techniques, decreasing sensor costs, and wide-scale adoption have made these approaches more accessible than ever. However, after initial processing of data, present day methodologies are often overly simplistic, or require expert design of site-specific algorithms with fine-tuning of non-intuitive parameters that are time consuming to produce. In addition, current remote-sensing based workflows often do not utilize data from in-situ monitoring sensors, such as RTK-GNSS (Real-Time Kinematic Global Navigation Satellite Systems), inclinometers, or extensometers. Rather, survey data collected is processed and analyzed in isolation missing an opportunity to leverage the advantages of each data source to obtain a comprehensive understanding of the landslide. The goal of this work is to develop a new easily implementable surface displacement monitoring framework that fully utilizes data from both remotely sensed and in-situ data sources to achieve greater insight than from either data alone.

Methods: Two new computational techniques, combined with the development of low-cost, in-situ RTK-GNSS sensors have been created to advance landslide monitoring capabilities. First, a new automated method utilizing self-supervised learning to train an optical flow predictor network is used to derive landslide surface displacement information from sequential DEMs (Digital Elevation Models). Next, a network of low-cost RTK-GNSS sensors is developed and deployed to two landslides on the Oregon Coast over a three-year period to collect high frequency (30-minute interval) data on landslide displacement. Lastly, leveraging these approaches, a computationally efficient novel method of fusing remotely-sensed and in-situ monitoring data (specifically RTK-GNSS) using an spatio-temporal Kalman filter to produce a high-spatial high-temporal interpolation of deformation is developed, named LADI – Landslide displacement interpolation.

Results: The first method of deriving dense landslide surface displacements is tested against a detailed ground truth dataset and compared with other methodologies from the literature and shown to yield superior performance with an End Point Error RMSE = 0.026m. This method is demonstrated on both lidar and SfM/MVS (structure from motion, multiview stereopsis), proving to be robust to both input data source, as well as the presence of vegetation artifacts. LADI is demonstrated to be capable of performing accurate spatial interpolation across a landslide using a single RTK-GNSS control point using remote-sensing derived calibration data. On the test data accessed, LADI is demonstrated to have superior spatial interpolation performance over conventional interpolation approaches when data are sparse (e.g., < 16 control points).

Conclusions: By combining the proposed approaches along with RTK-GNSS sensors, a viable framework for high-spatial, high-temporal surface monitoring of landslides is presented. This proposed monitoring framework is demonstrated to achieve reliable and accurate performance while lowering required survey frequency, and utilizing low-cost in-situ sensors. This enables a viable framework for implementation in active landslides for both scientific and practical monitoring applications.

LANDSLIDES ON CATACLINAL SLOPES IN ANISOTROPIC FLYSCH ROCKS. STUDY FROM THE OUTER CARPATHIANS (POLAND)

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Purpose: Methods of structural geology are not commonly applied for studying of the landslide development in flysch rocks in the Outer Carpathians. However, such work may contribute as to better understanding the development of the landslides and help to prevent the negative effects of mass movements. For this reason, it is important to determine the influence of morphostructural factors on the geometry of landslides and to identify the types of displacements occurring under conditions of anisotropy of bedrock.

Methods: The study was carried out for selected sample areas in Beskid Śląski and Bieszczady Mountains and was based on classical methods of structural geology and analysis of the digital terrain model from airborne LiDAR data. Geometric relationships between relief of terrain surface and bedrock structure were analysed, and the TOBIA classification (Topographic Bedding Intersection Angle) was used to determine the slope types. The kinematics of slides were then determined based on the orientation of the slope relative to the orientation of the tectonic discontinuities and angle of internal friction of the rocks. To classify gravitational displacements the cross-sections through landslide slopes and a discriminant diagram of landslide relief features were used.

Results: Geometrical and kinematic analyses of the landslides revealed their complex internal structure, resulting from the anisotropy of the bedrock and the specific orientation of the tectonic discontinuities. The study area is dominated by landslides of the complex type, with pronounced extensional structures in the detachment zone and compressional structures in the accumulation zone. Many landslides occupy large areas and can be classified as rock slope deformations or deep-seated landslides. The detailed analysis shows that the relationship between terrain relief and bedrock structure is manifested by a high proportion of cataclinal slopes (35%), which are significantly affected by mass movements (87% of the total landslide area). In addition, the strong dependence of the relief on the orthogonal arrangement of joints and faults in the bedrock is usually manifested by numerous linear, perpendicular scarps and landslide fissures. The observed dependence of landslides on the bedrock structure and the characteristic regularity of their shapes has led to the distinction of 3 types of so called 'drawer structures': A - single (simple, translational) and multiple B and C. In type B, the landslide development changes the type of displacement from translational to rotational and thus causes the folding and thrusting of the displaced rock packages. In type C, displacements were realised by the ramp connection of sliding surfaces.

Conclusions: Classical methods of structural analysis have been proven as very useful for the study of landslides in flysch rocks. The strong dependence of the relief on the structure of the bedrock is clearly visible on cataclinal slopes. The presence of rocks with anisotropy causes changes in the type of displacement, which can be described with the concept of 'drawer structures'. The results of the study provide better understanding of the complex structure of landslides and can be used as a model for the further research and engineering practice.

DEEP-SEATED ROCK SLIDE - IMPLICATIONS OF ENGINEERING GEOLOGICAL MODELS ON STABILITY AND HAZARD ASSESSMENT

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Purpose: Deep-seated rock slides are common hazards that can endanger human life, settlement areas and critical infrastructure such as highways, railways and dam reservoirs. In order to perform a reliable hazard assessment of these rock slides the failure geometry, the kinematics, the temporal-variable deformation behaviour and the hydrogeological situation need to be understood profoundly. Generally, engineering geological models are obtained from surface investigations such as geomorphological-geological mapping, remote sensing and slope deformation monitoring. Ideally, subsurface explorations data based on drillings and investigation drifts are also available to improve the models, especially when critical infrastructure or settlements are threatened. However, it must be considered that in many cases it is not possible to carry out subsurface investigations due to high costs and/or safety-related issues. Nevertheless, reliable hazard assessments are needed here as well. This contribution focusses on the creation and uncertainties of engineering geological models of deep-seated rock slides, especially when subsurface investigations are not available. It will be shown how such models can be developed by a combined analysis of surface data based on different methods. The conceptual basis for this is the assumption that rock mass deformations in the subsurface lead to characteristic structures on the slope surface.

Methods: Based on several cases studies in metamorphic rock masses from the Austrian Alps a wide range of methods useful for the development of engineering geological models are presented, comprising geological-geomorphological mapping, structural analysis, remote sensing and deformation monitoring. Special attention is given to numerical modelling based on the discrete element method, which is well suited to simulate large and discrete surface and internal deformations of the rock slide.

Results: Comprehensive investigation of several case studies emphasizes the impact of the structural inventory on the final geometry of the rock slide, the shape of the basal shear zone and the formation of different slabs. Furthermore, it could be shown by numerical modelling that the shape of the basal shear zone and the geological structures have a major influence on the deformation characteristics of the rock slide, e.g. resulting in up-hill facing scarps, graben structures, extensional zones on the surface. Due to the high complexity of some rock slides, models based on surface and subsurface investigations may change with time as investigation progresses.

Conclusions: Validated by subsurface investigations, herein it can be shown that the development of reliable engineering geological models is possible through surface investigations and a better understanding of the deformation mechanism can be obtained. However, uncertainties regarding the depth and shape of the basal shear zone and the geometry of slabs exits and must be considered for subsequent hazard assessment studies or stability analysis.

ASSESSING THE EFFICACY OF DIGITAL PARTICLE IMAGE VELOCIMETRY IN STUDYING THE REACTIVATION OF FLOW-LIKE LANDSLIDES IN CONDITIONS OF SUBOPTIMAL IMAGE QUALITY

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Purpose: The mechanisms and dynamics underlying the behaviour of flow-like landslide kinematics, including faster debris flows and slower earthflows, are still subject to debate and not fully understood in the literature, both in terms of field reactivations and laboratory physical models. In each case, camera recordings, or time-lapse videos for slower movements, have been shown to provide valuable insight into the rheology and the evolution of internal structures of documented phenomena. The Digital Particle Image Velocimetry (DPIV) analysis technique has been widely employed in the literature to reconstruct velocity and deformation fields of laboratory physical models under controlled and ideal conditions. However, the resolution of field camera footage frequently falls short of being optimal due to weather and lighting conditions as well as recording geometry, which can negatively impact the final image quality.

Methods: To assess the capabilities of the DPIV analysis technique and establish a workflow methodology that could be transferred to the field for studying flow-like landslide reactivations, a series of laboratory flume experiments was undertaken between the landslide flume facilities of the Department of Civil and Structural Engineering at the University of Sheffield and the British Geological Survey office in Keyworth. The experimental design was developed to observe and record quasi-steady dry granular flows, and reconstruct their velocity and deformation fields. The camera recordings were carried out from three different perspectives: two ideal views, normal to the flume lateral wall and basal chute surfaces, respectively, and a more oblique one to mimic the typical field recording geometry. The use of different performance sensors, ranging from powerful cameras with high frames per second to lower-cost ones, has enabled exploring a broad spectrum of image quality and resolution sets, bridging the gap between ideal experimental conditions and actual field recordings.

Results: The deformation and velocity fields resulting from the analysis of the observed flows were evaluated along fixed reference sections generating a set of velocity profiles recorded from each view angle. Comparing the experimental velocity distributions consistently revealed a good correlation between those taken vertically and at the surface, despite the different cameras setup, suggesting that the adopted methodology is capable of estimating and describing flow dynamics, even when image quality is suboptimal. Additionally, the obtained results highlight that footage acquired from a non-zenithal perspective can be effectively used, after appropriate image distortion corrections.

Conclusions: The experimental outcomes highlight the potential of the DPIV technique to estimate and reconstruct the deformation and velocity fields of flows, even when the image quality and the view angles are not ideal. These findings suggest that the adopted methodology could be effectively transferred to the field to investigate flow-like landslides reactivations.

SESSION 1.1

INTERNATIONAL PROGRAMME ON LANDSLIDES AND GLOBAL AND INTERNATIONAL ACTIVITIES FOR KLC2020 (part II)

DEVELOPMENT OF EARLY WARNING TECHNOLOGY FOR RAIN-INDUCED RAPID AND LONG TRAVELING LANDSLIDES IN SRI LANKA - PREDICT CATASTROPHIC LANDSLIDES A DAY IN ADVANCE

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Purpose: Landslides frequently occur in Sri Lanka, where there has been a marked increase in torrential rainfall with the onset of climate change. Thus, it is a pressing need to predict the occurrence and range of rapid and long-traveling landslides a day in advance. The 5-year SATRES Project “Project RRLL (IPL-249)” was officially launched in 2020; RRLL stands for “Rain-induced, Rapid, and Long traveling Landslide.” This project develops a system for early transmission of information predicting landslides and for supporting risk assessment, incorporating cutting-edge technology that forecasts maximum accumulated rainfall within a 500-meter grid. Considering the influence of orographic turbulence in mountainous areas, it predicts the occurrence, spread, and range of landslides due to unsaturated seepage in highly weathered soil on hillsides in tropical forests.

Methods: The Joint coordination committee (JCC) is the main implementing body for the project, where we have the Secretariat of the International Consortium on Landslides (ICL) on the Japanese side and the National Building Research Organization on the Sri Lankan side as its core. We also have members from the Tokyo Institute of Technology (TIT), Kyoto University, Forestry, and Forest Products Research Institute (FFPRI), Kochi University in Japan, the Disaster Management Center (DMC), Department of Meteorology (DOM), and the Department of Irrigation (DOI), and the Central Engineering Consultancy Bureau (CECB) in Sri Lanka. Furthermore, relevant individual researchers from major universities, etc., in Japan and Sri Lanka join the project to develop individual technologies.

Results: The key technologies to develop are (No. 1) the technology for one-day-ahead prediction of heavy rainfalls, (No. 2) the technology for assessing groundwater pressure buildup and initiation of RRLL as well as its flowing dynamics, (No. 3) the technology for the last-mile relaying of Early Warnings and thus strengthening the RRLL risk communication protocol. For No. 1, the influence of orographic turbulence in mountainous areas, which often increases cumulative rains, particularly on mountain slopes against the wind, has successfully been reproduced in simulations on affordable workstations, using an atmosphere-ocean coupled model (Multi-Scale Simulator for the Geo-environment, MSSG). For No. 2, LS-Rapid successfully reproduced initiations and runouts of large RRLLs in both Sri Lanka and Japan. For No. 3, i.e., the last-mile relaying of early warnings, an augmented reality system is being developed for shearing predicted risk information and providing public education. Its early-generation model is nearly completed.

Conclusions: As stated above, developing critical technologies for the project is well on track. The technology developed in this project, which predicts rainfall and the occurrence and range of landslides, is expected to be used in various fields, such as in the mitigation of rapid and long-traveling landslides, flood control, and disaster prevention in rural and urban areas in Sri Lanka, as well as in other Southeast Asian nations in monsoon regions, where similar disasters are common.

RECENT INITIATIVES FOR ENHANCING LANDSLIDE RISK MANAGEMENT IN SRI LANKA

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Purpose: Landslides are a fatal natural cause in Sri Lanka, which needs to be determined and managed adeptly. A significant number of attempts were made to reduce the risks in landslide-prone areas. Numerous landslide risk sites exist to apply landslide risk reduction techniques. Therefore, it needs to be understood the effectiveness of the risk reduction approaches practiced in the preceding years and the applicability of those techniques to identify risk locations in the foreseeable future. Thus, this study aims to review recent landslide risk management initiatives for creating safer shelters in Sri Lanka.

Methods: Several risk reduction initiatives applications were gathered in the past few, and each project activity was scrutinized. A matrix was developed based on the risk reduction initiatives, and empirical evaluation was conducted to study the impact performance of each activity. The Sendai framework was considered the evaluation criteria, and results were generated consequently.

Results: The understanding of risk is considered in two major steps: probabilistic maps and field observations. Initially, a hazard map was generated through a multi-criteria approach and converted to a risk map. This risk map was further intensified by including automated flow path simulations, and field observations were advanced by arranging a systematic data collection procedure. Structural and non-structural mitigation measures were applied as risk-treating options. The structural mitigation methods were initially outlined and made even more robust with technological improvements, such as Soil nailing, Mass Concrete wall, RRM wall, Reinforce concrete wall, and Gabion wall. Non-structural mitigation approaches were implemented in several locations, including land-use planning, effective landslide early warnings, and forming community groups. The acceptance of a nature-based solution rose in popularity because of its other advantages and tried in numerous areas. The area-based alert system was implemented by recognizing the rainfall threshold values that induce accurate landslide warnings to the public. Resettlement project activities were implemented with multiple options to eliminate the risk, and 15,000 buildings were identified to be resettled. Several policies were enforced to manage the built environment, particularly on mountainous slopes, to reduce the effect of land modification.

Conclusion: Initiatives of landslide prevention come in many directions. The technique selection is mainly driven by multiple factors, such as the importance of the location, livelihood, and financial–social benefits. However, it is deemed with numerous challenges, such as acquiring knowledge, technology, machinery capacities, and skilled labours. Therefore, preventive measures are required to minimise the landslide risk eventually. Managing landslide-prone or affected zones becomes another challenge. These lands should be strictly monitored and managed, but they could underpin because of a lack of knowledge transformation of communities and stakeholders. Therefore, a robust risk communication protocol needs to be implemented in the future. The research and development on landslide risk reduction should be improved on recognising the hazards, risk management techniques, risk evaluations, hazard resistance, and risk evaluation capabilities. Also, funding opportunities that promote research and development are required with the changing consequences of climate change and rapid urbanisation.

INTRODUCING JAPANESE LANDSLIDE WARNING SYSTEM TO SRI LANKA: FIELD SURVEY FOR ANALYZING THE AVAILABILITY OF MAP INTERPRETATION FOR SUCCESSFUL TECHNOLOGY TRANSFER

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Purpose: The central highland in Sri Lanka has the landslide prone geo-hydrological condition originally. Since the area have been developed for agriculture and human settlements, series of landslide occurred in the mid-1980s. Landslide is a natural hazard triggered by rainfall and geological condition. Since the topography such as mountain with steep slope and weather such as high precipitation are similar in Japan and Sri Lanka, similar landslide phenomena have been seen. One of the common landslide phenomena is Rain-induced Rapid and Long-travelling Landslide (RRLL). Recently landslide disaster risk reduction technologies have been developed in Sri Lanka, and foreign technologies have been introduced. Early warning and evacuation using hazard zonation map is a major system for landslide disaster risk reduction both in Japan and Sri Lanka. Japan have already developed and used the early warning and evacuation system using hazard zonation map. Since the system have been developed based on the Japan's socio-economic background, it is used successfully in Japan. Thus, when this Japanese technology is used in Sri Lanka, in addition to the engineers' availability of mastering technologies, local people's availability of accepting the technology is also examined before the project start.

Methods: In this research, social background for introducing Japan's early warning system in Sri Lanka is analyzed based on the literature review and field survey at Arayanake, especially focusing on the availability of map interpretation. Based on the literature review, it is said the map education is available. The questionnaire survey was conducted at Arayanake to know the local people's perception of landslide disaster risk reduction. There are five categories of questions as follows:

1. Demographic information: Q1-11
2. Livelihood: Q12-14
3. Experience of landslide: Q15
4. Hazard map and early warning: Q16-29
5. External help: Q30-36

Results: In the selected areas, there were 50 respondents, 16 males and 34 females. Based on the survey, it shows the availability of map interpretation. Twenty-eight respondents answered that they saw the hazard map of their living area. They are well educated to interpret the map, and many of the 28 people can tell the locations of their houses on the hazard map.

Conclusions: Since the availability of map interpretation is the must for landslide early warning system using hazard map, there is possibility that Japanese type early warning and evacuation using hazard zonation map is effectively used in Sri Lanka. However, hazard map in Japan includes the evacuation area and route, the survey for evacuation area and route is needed. In addition, information system for warning is also needed to be surveyed for utilizing the Japanese landslide warning system in Sri Lanka.

RAIN-INDUCED RAPID AND LONG-TRAVELLING LANDSLIDES- A CASE STUDY IN THE ATAMI DISTRICT, SHIZUOKA PREFECTURE, JAPAN

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Purpose: From 1–3 July 2021, extreme rainfall occurred in the Atami District, Shizuoka Prefecture, Japan, causing catastrophic debris flow around 10:30 on 3 July 2021. The Atami debris flow claimed 27 lives, with one missing and three injuries and destroyed 54 houses as of 10 February 2022 (Shizuoka Prefecture 2022). This research aims to study the initiation mechanism and behaviour of the debris flow triggered by the extreme rainfall in Atami. This catastrophic event was used to validate the tools for evaluating how torrential rain would trigger a rapid and long-travelling landslide which are the critical technologies for the SATREPS project titled Development of early warning technology of rain-induced rapid and long-travelling landslides in Sri Lanka (RRLL).

Methods: On 17 January 2022, International Consortium on Landslides (ICL) researchers investigated the landslide area. A sample was taken immediately behind the exposed scar and sent to the Kyoto ICL-SATREPS office for ring shear tests. The ring-shear apparatus (ICL-2) was used to reproduce soil collapse, the sliding surface's formation, and the landslide's steady-state motion. The rainfall-induced pore-water pressures were calculated using the Slope-Infiltration-Distributed Equilibrium (SLIDE) model developed by Liao et al. (2010). The integrated simulation model LS-RAPID was used to simulate landslide motion using landslide dynamic parameters obtained from the ring shear test and pore-water pressure ratio from the SLIDE model.

Results: An undrained speed control test was conducted at a normal stress of 200 kPa, which corresponded to the landslide initiation in the field. The measured steady-state shear resistance was 30 kPa. The friction angle of the peak failure line and friction during motion were 30.5° and 16.4°, respectively. The low values of the steady-state shear resistance and the friction during motion may contribute to Atami's rapid and long-travelling debris flow. LS-RAPID results show that when the pore pressure ratio reaches 0.25 at 10:40:00 am on 3 July 2021, failure starts from the top of the landslide source area. After 13 seconds, at 10:40:13s, the entire landslide mass is formed. Then, it starts to move downwards towards the residential area reaching this area at 10:41:27.The landslide mass stops moving and is entirely deposited at 10:43:00.

Conclusions: The results demonstrate that the LS-RAPID model predicts a similar hazard area to that observed in the field investigation. In addition, the time of landslide occurrence estimated from the rainfall record and the LS-RAPID simulation is close to the event timing. The ring shear testing, the SLIDE model, and the LS-RAPID model may serve as tools to assess the pore-water pressure build-up, initiation and motion of a rain-induced rapid and long-travelling landslide.

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SLOPE STABILITY ANALYSIS UNDER THE INTEGRATED EFFECTS FROM GROUNDWATER AND RAINFALL - CENTRIFUGE MODELING

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Purpose: Due to the serious harm, they cause to society and the economy, landslides become an infamous topic. In recent years, numerous measures, particularly the creation of landslide early warning systems, have been taken to reduce the damages brought on by slope behavior. Certainly, rainfall is one of the most important external factors that lower soil suction and shear strength, which in turn leads to shallow landslides. However, the absence of a more thorough hydrological process involving subterraneous flows, means that temporal predictability still poses a challenge. Understanding the complex behavior of pre-existing groundwater table and its surcharge during a rainfall event is essential for strengthening the landslide early warning mechanism. Therefore, the goal of this paper is to investigate how the initial condition of the soil-bedrock interface, which is controlled by an existing groundwater table, affects the slope that is exposed to rainfall infiltration afterward.

Methods: Physical modeling using geotechnical centrifuge technique was employed to assess the impact of a pre-existing groundwater table on a slope exposed to rainfall. An experimental soil container was created to facilitate the simultaneous functioning of groundwater and rainfall. In this experiment, Masado soil, a well-graded silty sand was used. Porewater pressure transducers (PPTs) were buried during the construction of the slope to collect data on the distribution of pore water pressure, and markers were positioned between the soil slope and the transparent window to record displacements. In this experiment, before applying rainfall the groundwater table was first simulated until PPTs' response became constant with time and then rainfall was applied. Accordingly, five identical cases (test 01) were conducted during this test series. In addition to test 01, test 02 was conducted by exposing only to rainfall to compare the landslide characteristics.

Results: Landslide characteristics of five identical cases in test 01 resulted a similar behavior among each tested case with respect to porewater pressure response and deformation. As expected, test 01 had a quicker failure time whereas test 02 needed more time to fail. The porewater pressure under the combined effect of groundwater and rainfall recorded a simultaneous response upon rainfall while the slope exposed only to rainfall showed a sequential response. Further, in test 01 the rate of change in porewater pressure suggested the possibility of creating a surcharge flow upon rainfall infiltration. The slip surface profiles, and volume of landslides demonstrated prominent distinctions between the two tests.

Conclusions: This study focuses on emphasizing the importance of pre-existing groundwater table in the generation of landslides. The results concluded that pre-existing groundwater table could lead to a quicker and a voluminous landslide compared to a slope only exposed to rainfall.

DEVELOPMENT OF A NEW INTEGRATED EARTHQUAKE-GROUND TILT-RAINFALL MONITORING SYSTEM IN SRI LANKA

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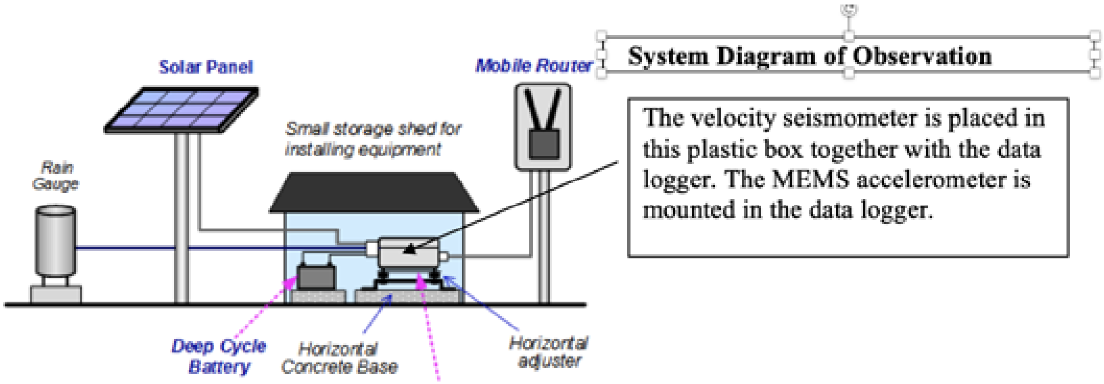
Purpose: Extreme rainfall and earthquake events have become more frequent worldwide. The landslide risk triggered by small earthquakes during / after rainfalls is expected to increase. To study the risk of rain-earthquake compound disasters in Sri Lanka where small earthquakes are increasing, we have developed a new integrated earthquake-ground tilt-rainfall monitoring system (IETR).

Methods: We have installed the IETR monitoring system in the geomorphologically identified landslide blocks in Alanayake, Kandy and Athwelthota areas in Sri Lanka. A 3-axis MEMS (Micro Electro Mechanical Systems) accelerometer is used to measure small to large earthquake ground motions at the landslide site, and a high-sensitivity 3-axis velocity seismic sensor is used to measure micro-earthquake motions and microtremors. The MEMS accelerometer is also used to monitor the tilt of the landslide ground, which is important for predicting landslide occurrence and estimating landslide ground movement. The observation points were selected on an unstable slope with a high possibility of ground sliding and on a stable exposed bed rock outside the landslide block. Observation data shall be transmitted from each site to the data server via a mobile network and recorded in an SD card. The power supply at the observation sites is a deep-cycle storage battery with solar panel. Array observations using microtremors are carried out to investigate the ground structure up to the basement rock directly below the landslide ground.



List of observation stations.

Station No: 001-005	Aranayake 1- Aranayake 5	including 2 bed rock sites.
Station No: 006-007	Kandy 1- Kandy 2	including 1 bed rock site
Station No: 008-009	Athwelthota 1- Athwelthota 2	including 1 bed rock site
Station No: 010	Univ. of Peradeniya 1	

Results and Conclusions: Based on microtremors, seismic motions and tilting at exposed bed rock sites, vibration characteristics and tilting specific to the landslide ground are extracted. These are discussed in terms of landslide prediction. In particular, the discussion focuses on the vibration characteristics and the tilting before and after heavy rainfall events.

SUPER-RESOLUTION SIMULATION FOR REAL-TIME OPERATIONAL PREDICTIONS OF OROGRAPHIC PRECIPITATION IN SRI LANKA

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Purpose: Super-resolution simulation for real-time operational predictions of orographic precipitation in Sri-Lanka.

Methods: We adopt the super-resolution (SR) simulation system (Onishi et al., 2019), which utilizes the CNN-based SR technology, for real-time operational predictions of orographic rainfall in Sri Lanka. First, we used the multiscale weather model, MSSG (Multi-Scale Simulator for the Geoenvironment; Takahashi et al., 2007, 2013; Onishi and Takahashi, 2012), to run high-resolution orographic rainfall simulations for Sri Lanka. The rainfall simulation adopted the new cloud microphysical parameterization that can consider the effect of atmospheric turbulence on rainfall generation processes (Onishi and Seifert, 2016; Seifert and Onishi, 2016), which enables us to consider the impact of boundary layer turbulence on orographic precipitation (i.e, mountain rainfalls). Second, the obtained high-resolution results were used for training a super-resolution neural network (SRNN). The trained SRNN can downscale, i.e., upconvert, the low-resolution (LR; 2km horizontal resolution) rainfall maps into high-resolution (HR; 500m horizontal resolution) ones.

Results: We have confirmed that the trained SRNN outperforms the algebraic interpolations for downscaling the LR rainfall maps into HR ones. It is also confirmed that the present SR simulation system can realize real-time high-fidelity prediction maps on a desktop computer in local offices, specifically it can produce 24-hour predictions of rainfall maps with 500m horizontal resolution within an hour.

Conclusions: We have developed a reliable rainfall prediction system, based on the super-resolution (SR) simulation, to be incorporated with an early-warning system for rapid and long travelling landslides in Sri Lanka. The present system consists of low-resolution (LR) physics-based weather simulation and SR neural network to downscale LR rainfall maps into high-resolution (HR) ones. This super-resolution simulation system works as expected and it enables the present system produce 24-hour HR predictions within an hour. The HR rainfall prediction maps are then transferred to the landslide simulation model and to the early warning system. The integrated system will help construct a safe society free from victims due to landslides.

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POTENTIAL DAMAGE ZONE PREDICTION OF RAIN-INDUCED RAPID AND LONG TRAVELING LANDSLIDES IN SRI LANKA, BASED UPON DEBRIS FLOW ANALYSIS COMBINING CELLULAR AUTOMATION AND MULTI-AGENT MODELS

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Purpose: A Landslide is one of the geo-dynamic processes that naturally shape the geomorphology of the earth. Among various natural hazards, landslides have been attracting increasing attention worldwide due to their increasing and serious impacts on human lives and the economy. Currently, major measures for landslide disaster management taken by the National Building Research Organization, Sri Lanka are (1) landslide susceptibility mapping based upon terrain factors (2) issuing landslide warnings and relaying them timely to the last mile, namely communities at risk through the Disaster Management Centre with community-based networks and (3) evacuation practices. The accurate potential damage zone prediction is a pressing need through the geospatial highlighting of downslopes vulnerable to landslides.

Methods: Assessing the geospatial susceptible zones for landslide initiations is introduced through the combining approach of the geomorphological hill-shade with slope map analysis by ArcGIS and the highest landslide susceptibility zones from Landslide susceptibility maps produced by the National Building Research Organization. The next step is to predict the potential damage zone in downslopes. The complete mechanism of unstable mass movement is investigated through the analysis of (1) the debris distribution variation along the landslide runout by the combining approach of picture-based analysis and sieve analysis, (2) the debris propagation mechanism by flume test, (3) surface morphology by Light Detection And Ranging data, and (4) stopping mechanism through mobility index. The multiple surveys and investigations of pilot sites that were introduced from the SATREPS project; Aranayake, Athweltota, and some more in Japan are used for the model development. Those listed above are important data for the simulation of the runout distances of Rain-Induced Rapid and Long Traveling Landslides. For these simulations, we will develop a combined model using Cellular Automaton (CA) and Multi-Agent (MA) models. The mechanical features of the soil/debris will be implemented in the local interaction rules that describe interactions among neighboring agents (soils, water, etc.) on the grid structure of the Cellular Automata model. These models are promising to allow us to simulate the flows of fluidized debris slurries which are often mixtures of water, sand, gravel, etc., and will be described as agents in each cell on the grid structure of Cellular Automation covering the 3D terrain of the target area.

Results: The main outcomes of the study are the geospatial susceptible zones for landslide initiations and the potential damage zone prediction of Rain-Induced Rapid and Long Traveling Landslides. The importance of this approach can be described as the combined model of Cellular Automaton and Multi-Agent leading to time-saving through multiple point simulating and using local interaction rules for simulating. The accuracy of this combined model will be evaluated by the overall evaluation factor (Ω) through back analysis of pilot sites.

Conclusions: Developing the method combining Cellular Automaton and Multi-Agent models to simulate downslope movements of fluidized debris mass is thus vital for assessing potential damage zones and will help disaster management activities in not only Sri Lanka and Japan but also other countries suffering from heavy rains.

COMPARISON ON RESIDUAL SHEAR STRENGTH OF LANDSLIDE SOIL USING UNDRAINED RING SHEAR APPARATUS

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Purpose: One of the main purpose of the project "Rain-induced Rapid and Long-travelling Landslides" under Science and Technology Research Partnership for Sustainable Development (SATREPS) is to identify the possible causes and contributing factors of the landslides happened in Sri Lanka. To study landslide dynamics, it is important to simulating the entire process of the landslides and for this purpose undrained ring shear apparatus is a major tool used in the analysis of residual shear strength of soil. In general, the residual soil in Sri Lanka has higher content of silts and clay percentage. In this study the behavior of residual shear strength of soil in Athwelthota landslide is assessed.

Methods: ICL – 2 Undrained ring shear apparatus was received to National Building Research Organization (NBRO) in 2022, and it can simulate the landslide process within the apparatus with a maximum loading capacity of 1000 kPa. For the testing program, the disturb samples were collected and tests under different testing conditions such as such as shear speed control, shear displacement control and porewater pressure control to compare the behavior of the soil.

Results: Based on the experimental results, the friction angle at peak (ϕp), mobilized friction angle at failure (ϕm), steady state shear resistance (τss), shear displacement at the start of strength reduction (DL) and shear displacement at the start of steady state (DU) of the tested soil samples which is necessary for the simulations of landslides will be analyzed.

Conclusions: The results of this study will provide an important reference to understand the behavior of Sri Lankan residual soil under different test conditions. Undrained ring shear testing could be used as a main tool of studying soil conditions which are prone to landslides.

ASSESSING THE POTENTIAL RAPID AND LONG TRAVELLING LANDSLIDES IN SRI LANKA - A CASE STUDY OF ATHWELTHOTA LANDSLIDE

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Purpose: Landslides are a significant natural hazard in Sri Lanka, causing significant damage to infrastructure, property, and loss of life. The country is highly susceptible to landslides due to its mountainous terrain, frequent heavy rainfall, and poor land-use practices. One of the objectives of the project “Rain induced Rapid and Long-travelling Landslides”, between International Consortium of Landslide (ICL) and National Building Research Organisation (NBRO) is to identify the causes and contributing factors of the landslide happened in Athwelthota in May 2017, which is one of the most devastating landslides in the country’s recent history, resulting in several fatalities and significant damage. Therefore, this study focuses on the dynamics of the Athwelthota past landslide and the potential hazard of the surrounding slopes.

Methods: The study utilized LS-RAPID numerical simulation software to estimate both past and potential landslide hazards in the area. To examine the physical properties of the soil, samples from the study area will be tested using undrained ring-shear testing. The results of the ring-shear tests will be used to calibrate the LS-RAPID landslide model for the past landslide simulation, which was then reproduced using available field evidence and remote sensing data. The calibrated model is likely to simulate two nearby potential slopes to assess the hazard by assuming the slip surface.

Results: The LS-RAPID model is expected to reproduce the past landslide and estimate the landslide hazard in the study area, indicating a high probability of landslides occurring in locations with steep slopes. Additionally, the study will discuss the triggering mechanism and causes of the past landslide and the two nearby slopes in contrast to factors such as heavy rainfall and groundwater.

Conclusions: In conclusion, the Athwelthota landslide was found to be a complex phenomenon involving multiple factors such as rainfall and groundwater table fluctuations. The LS-RAPID model is a useful tool in assessing landslide hazards and identifying vulnerable areas under simplified representative conditions.

ASSESSMENT OF THE STRUCTURAL GEOLOGICAL, HYDROGEOLOGICAL, AND GEOMORPHOLOGICAL RELATIONSHIP THAT CONTRIBUTE TO THE FORMATION OF AN UNSTABLE SLOPE IN THE ATHWELTHOTA LANDSLIDE LOCATED IN BADURALIYA, SRI LANKA

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Purpose: The National Building Research Organization of Sri Lanka (NBRO) and the International Consortium on Landslides (ICL) have initiated a 5-year research project called “Rain-induced Rapid and Long-travelling Landslides” in collaboration with the framework of SATREPS. The objective of the project is to develop an early warning technology for rain-induced rapid and long-traveling landslides. A landslide that occurred in Athwelthota, Sri Lanka in May 2017 has been selected as one of the pilot sites for field studies. Equal attention shall be paid to external features such as rainfall infiltration and slopes’ in-situ conditions for landslide initiation. Therefore, in this study, an attempt has been made to understand the relationship between structural geological features and geomorphological features in and around the Athwelthota landslide area for comprehending the causes of landslides. This study focuses to determine the contribution of in-situ features to the occurrence of landslides.

Methods: Topographical variations were analyzed using satellite maps, lidar images, and survey maps of the site. The study involved a field survey to collect samples of structural geological features such as dip, dip direction, and fracture and joint indexes present at the site. Seismic surveys and borehole investigations were undertaken to assess the subsurface condition. In addition to the borehole water level meters hydrogeological surveys were also conducted to determine the features affecting the groundwater table under natural recharge and discharge mechanisms.

Results: The landslide has been moved to the North-East direction of the slope creating a deep valley along a former ephemeral valley. The former landslide slope has existed as a concaved slope with parallel minor valleys starting from the top of the mountain. The steep slope can be found from the main escarp of the landslide (35 to 43 degrees). The two streams starting from the middle of the main and minor landslides are discharging through a geological discontinuity. As per the borehole investigation data, sandy silt soil overburden extends up to 12 m depth while highly weathered rock extended up to 16.5 m. Seismic survey results show that the rock level is varying significantly over the landslide area. The study found that three types of joint sets (J1, J2, and J3) exist within the landslide region. Hydrogeological connection through the joint plains that exist parallel to the landslide axis (J1) could be significantly recharged the landslide body rising the groundwater table to the shallow depths.

Conclusions: It was realized that topography, drainage patterns, and structural geological conditions around the Athwelthota landslide play a vital role in landslide failure, similar to rainfall infiltration. These features could accelerate the landslide initiation and enlarge the failure volume. Therefore, proper field assessments are always encouraged for vulnerable sites such as Athwelthota landslide.

Key Words: Athwelthota landslide, structural geology, hydrogeology, geomorphology

INTRODUCING A MECHANISM TO MANAGE THE RISK ASSOCIATED WITH "RAIN-INDUCED, RAPID, AND LONG TRAVELING LANDSLIDES" (RRLL) IN SRI LANKA

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Purpose: Landslides are one of the major natural hazard occur mainly in the central highlands of Sri Lanka, which are controlled by the geologic, geomorphologic, hydrologic and land-use and triggered by rainfall. With the result of recent global climate changes, Sri Lanka has experienced extreme rainfall events and the resultant "Rain-induced, Rapid, and Long traveling Landslide" (RRLL) which caused severe environmental, social and economic devastation compared to all types of landslides. The Morawakkanda landslide and the Aranayaka landslide are recent examples for RRLLs that cause huge deaths and property losses, and the death toll is about 150. The majority of the people, houses, and other properties in the Central Highlands are dispersed across the sloping land and are at risk from landslides, which have the potential to cause severe damage. Thus, this tragic situation has highlighted the importance of sophisticated mechanisms for prior identification of the total impact area for risk management through the means of risk assessment, issuing landslide early warnings, impact-based forecasting, and introducing proper land use guidelines and standards as needed.

Methods: This study is planned to achieve the above objectives and is carried out partially with the project SATREPS (Science and Technology Research Partnership for Sustainable Development). SATREPS is a collaborative research project implementing NBRO with the International Consortium on Landslides (ICL) within the framework of the Japan Science and Technology Agency. The project SATREPS was started in 2020 as a joint research effort with the objective of "Development of early warning technology for Rain-induced Rapid and Long-travelling Landslides". This project develops a mechanism for early transmission of information predicting landslides and for subsidiary risk assessment, incorporating cutting-edge technology that forecasts maximum accumulated rainfall within a 500-meter grid. Considering the influence of orographic turbulence in hilly areas, it forecasts the occurrence, spread, and range of landslides due to unsaturated seepage in highly weathered soil on hillsides. The first step to managing landslides is the identification of the entire impact area of landslides, including landslide initiation areas, flow path areas, and depositional areas. The National Building Research Organization (NBRO) of Sri Lanka's Landslide Hazard Zonation Maps (LHZM), produced at 1:50,000 and 1:10,000 scale, are used to identify the landslide initiation areas. The "Red Zone and Yellow Zone" methodology that was developed under the recently successfully completed project called "Project SABO," which was carried out as a collaborative project between NBRO and the Japan International Cooperation Agency (JICA), is used to identify flow paths and depositional area zones of the RRLL.

Results: Prior identification and prioritize the RRLL is done using the Combination of the above two outputs.

Conclusions: Supportive with the findings of the project SATREPS and SABO, risk assessment, one-day-ahead prediction of heavy rainfalls, last-mile relaying of early warnings, impact-based forecasting, and thus introducing proper land use guidelines and strengthening the RRLL risk communication protocol are all goals of the project.

SESSION 2.1

CASE STUDIES AND STATE OF THE ART ON LANDSLIDE MONITORING (part II)

DEVELOPMENT OF A GROUND DISPLACEMENT SENSOR FOR PREDICTION OF SEISMIC DEFORMATION OF EMBANKMENTS

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Purpose: Currently there are more than 50,000 embankments across the residential land in Japan. Among these, unstable embankments are considered to be in a higher proportion. Within this realm, assessment of the seismic resiliency of the existing embankments becomes very important. However, currently there are no established methods to carry out such an assessment. The purpose of this research is to develop a low-cost underground displacement sensor that can measure the minute deformation of embankments. The measured results from the developed sensor will be validated with the developed 3D FEM models considering the little displacements under small seismic excitations which can be used to predict the danger level associated with an existing embankment.

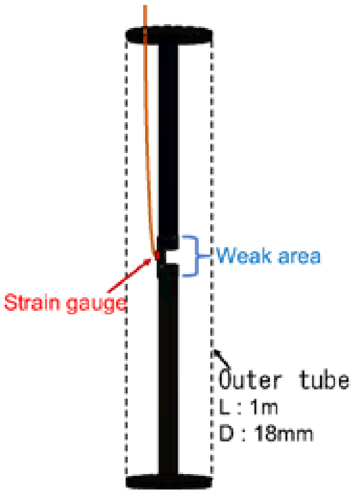

Fig. 1: 3D FEM model of the embankment.

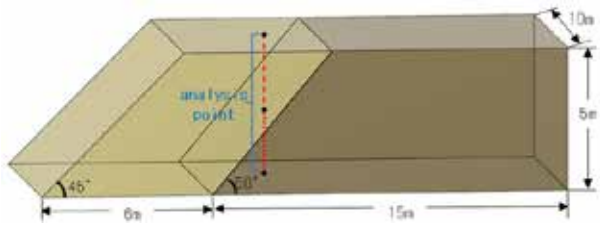

Fig. 2: Schematic diagram of the inclinometer.

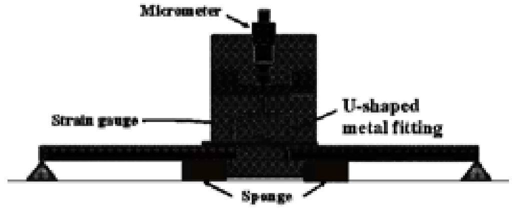

Fig. 3: Test for the developed sensor.

Methods: Step 1: Initially, several 3D FEM models were developed for the embankment having low seismic resiliency based on the provided in-situ geotechnical conditions of the existing embankments as shown in Figure 1. The deformations of the embankment subjected to earthquake motion ranging from small to large intensity earthquakes were obtained from the 3D FEM analysis and the results were analyzed. Step 2: The next step is to develop an inexpensive subsurface displacement sensor capable of measuring small deformations of the embankment during an earthquake. Figure 2 shows a schematic diagram of the sensor currently under development. To reduce the cost of system construction, this sensor consists of a cylindrical pipe buried in a borehole formed by a sounding test, and the movement of the ground is determined from the deformation of the pipe. To confirm the accuracy possessed by this sensor, tests were conducted as shown in Figure 3.

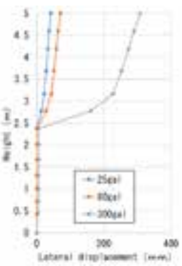

Fig. 4: Embankment movement.

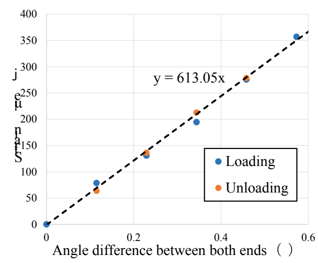

Fig. 5: Inclinometer verification.

Results: Figure 4 shows the deformation of the 3D model (see Figure 1) when subjected to a seismic motion: the ground surface displacement at 25 gal was 40 mm, and the embankment section tilted about 0.9° on average. This result confirms that in unstable embankments with a low seismic resistance, measurable ground deformation may occur even under relatively smaller seismic motion. The results further highlight the increasing lateral displacements with the increase in seismic intensity leading. The results indicate that if the deformation of an embankment subjected to a small seismic motion can be measured using our newly developed sensor, it may be possible to predict whether the embankment will slide or collapse during an earthquake. The results of the ground displacement tests for the newly developed sensor are shown in Figure 5. A linear relationship between angle and strain was obtained, which indicates the accuracy to be high as that of an expensive high-precision inclinometer.

Conclusions: The present study deals with the development of a novel ground displacement sensor to assess the seismic resiliency of existing unstable embankments, post initial validation with the 3D FEM models. With the deformation of the ground, the tilt angle in the weak area increases highlighting seismic stability of an embankment.

LANDSLIDE RISK ASSESSMENT IN KYRGYZ REPUBLIC

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Purpose: In 2021, the Asian Development Bank (ADB) approved the Landslide Risk Management Sector Project. It is ADB's first integrated preemptive landslide risk reduction investment that safeguards rural communities in the Kyrgyz Republic. The project will run from 2021 to 2028. The project will reduce the risk to communities and infrastructure from landslide events by (i) implementing landslide mitigation engineering measures, (ii) improving landslide monitoring systems, and (iii) strengthening capacity for landslide risk management. To support project preparation, ADB financed a multi-level landslide risk assessment (LRA) to inform the feasibility study and design. The Kyrgyz Republic is highly prone to landslides due to a complex interaction among geology, seismic activity, land cover, precipitation, human activity and climate change. According to the Ministry of Emergency Situations (MES), there are 4,554 landslides in the country, of which 1,186 are active and threatening over 540 settlements and 300 infrastructure assets. MES estimates that about 5,000 houses with a population of up to 30,000 people are under threat of potential landslides, mainly distributed in the southern regions of Osh and Jalal-Abad, the most densely populated, rural, and poorest of the country. The economic losses related to landslides and earthquakes are approximately 1%-1.5% of the gross domestic product, with a higher human impacts on vulnerable groups (i.e. low income, women, children, and elderly).

Methods: The methodology applied for the national-level LRA combines qualitative and quantitative analysis methods. The main steps of the work are: i) Analysis of available data and literature, with specific attention to the impact of climate change on landslide occurrence; ii) Analysis of available landslide inventories; iii) GIS processing of the available data; iv) Statistical analyses at national and regional scale in order to evaluate exposure; v) Expert review of a long list of approximately 250 sites proposed as potential subprojects for the investment project.

Results: A shortlist of 46 sites within the southern regions of Osh and Jalal-Abad was obtained after the selection process. Among them, 20 sites were selected for monitoring, for the remaining ones the implementation of remedial measures was recommended. Consolidation of literature maps, field investigations, such as drone photogrammetry, geophysical, geological and geomorphological surveys as well as physical asset surveys were carried out for each of the monitoring sites. Simplified runout models provided a tentative extent of the spreading area and the identification of exposed elements. A map of proposed instrumentation for early warning was prepared for each site. For what concerning active measures, a concept design of remedial work was proposed for a pilot site (Ayu Sai) after the performance of direct site investigations (geological mapping, boreholes, field and lab teste).

Conclusions: The work carried out supported the cost-benefit analysis for the finalization of the Landslide Risk Management Project budget, also considering the landslide return time estimated on the base of multi-temporal landslide inventories (Behling et al., 2014; Behling et al., 2016).

On the base of the results of the project, a Landslide Atlas of Kyrgyz Republic is being finalized and will be published soon.

MONITORING AND RISK MANAGEMENT OF UNSTABLE ROCK SLOPES IN NORWAY

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Nine unstable high risk rock slopes are currently being monitored continuously in Norway, and 19 additional slopes are monitored periodically. Monitoring is used to reduce risk in areas with large consequences of a failure and physical mitigation measures are not possible or excessively expensive. Almost 700 unstable slopes have been identified by the Geological Survey of Norway (NGU) and about 100 of these have been hazard and risk classified. Some of the unstable slopes may collapse into water bodies and form a tsunami wave. The hazard zones from these can be extensive and affect villages and towns, while other instabilities may fail in valleys and more limited hazard zones.

The Norwegian building codes requires that buildings of different security classes (garage, house, hotel or school) are outside hazard zones with different annual probabilities (1/100, 1/1000 and 1/5000). From 2011 an exception was added to the building codes allowing building in the hazard zones from tsunamis if the slope was continuously monitored. Strict requirements for the early-warning system needs to be in place. In 2022 and 2023 further changes were implemented, including exception in the building codes also for periodic monitored slopes and hazard zones due to direct impact of a landslide.

The Norwegian Water and Energy Directorate (NVE) is responsible for monitoring unstable rock slopes in Norway. Since the earliest monitoring network was set up at Åknes, a lot of experience has been obtained alongside development in monitoring technology. At the most recently instrumented sites of continuous monitoring, the focus is detailed monitoring of surface displacement in 3D – often using total station measuring a network of prisms and some carefully placed GPS antennas. Ground based InSAR, extensometers or lasers are used where suitable. Automatic alarms and daily check of data from all sites provides NVE with information necessary to evaluate the appropriate hazard level for each slope. Periodic monitoring is used for slopes with lower annual failure probability and an assumed longer acceleration phase prior to a collapse. Full scale continuous monitoring will not be cost effective for these sites. Corner reflectors, which are measured from radar satellites and processed daily using InSAR, forms the backbone in the periodic monitoring. We will present some examples of continuous and periodic monitoring of unstable rock slopes in Norway.

When the exception to the building codes is used, the requirements for both the periodic and continuous monitoring are strict. Redundancy in instrumentation, power supply and plans for upscaling the monitoring in addition to detailed emergency plans needs to be in place. However, as several communities were faced with severe restrictions for development, it was necessary to implement these exceptions. NVE finds that the current laws and monitoring methods in combination with an early warning system allows for safe communities with an acceptable risk.

ANALYSIS OF TREE GROWTH MICROSCOPICAL DISTURBANCES FOR LANDSLIDE MOVEMENT MONITORING AND THEIR POSSIBLE APPLICATION AS LOW-COST ENVIRONMENTALLY FRIENDLY SESNORS

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Purpose: We combine recent advances in microscopic tree growth disturbance analysis with long-term landslide movement monitoring to prepare a methodology for trees producing annual growth rings to be used as low-cost, environment-friendly, and densely spaced landslide movement sensors.

Methods: The standard dendrogeomorphological approach is complemented by the innovative microscopical anatomical analysis of tree rings. The latter analyzes a wide spectrum of anatomical features of woody cells (e.g., vessel or tracheid lumen area and shape, parameters of fibres and parenchyma cells, cell wall thickness) and compares them with the features from reference trees detecting the anatomical anomalies that are associated with landslide movements. Dendrochronologically defined events related to landslide movements are compared with the instrumental, surface (extenzometric, geodetic levelling) and sub-surface (inclinometry) monitoring to relate the microscopical anatomic tree response to specific movement magnitude. The geomorphological mapping defines the smallest spatial unit (called a morphogenetic unit) which is assumed to behave uniformly with respect to movement type and reactivation frequencies. This assumption is further tested by detailed geophysical research using electric resistivity tomography. So far, this approach was tested in highly heterogenous geological environments of Tertiary volcanic rocks or flysch deposits in the Czechia. The involved rocks have contrasting strength and hydrological properties and are typical with intense weathering producing expandible clay minerals.

Results: Results proved the sensitivity of anatomical growth disturbances to mm scale movements and their ability to identify prevailing movement characteristics (e.g., compression, extension, tilting, shallow planar sliding). It also improved the capability to record landslide activity with small recurrence intervals (e.g., months) as compared to the standard analyses. When the results obtained by microscopical analyses are combined with movement chronologies of “event” years defined by the standard dendrogeomorphological approach, spatially and temporarily complex information about landslide dynamics is available to be used for landslide hazard assessment.

Conclusions: We argue that in regions where vegetation prevents the effective use of remotely sensed data for landslide monitoring, this approach may represent a cost-effectively and climate-friendly option to collect applicable information about landslide movement dynamics and histories describing long time intervals, which are impossible to cover by any other monitoring technique. Although the dendrogeomorphological approach will never be able to replace precise, high reading-frequency and real-time instrumental monitoring, it represents a valuable addition to these methods.

COMPARING DEFORMATION MONITORING METHODS AT THE NORTH SLIDE, SOUTH-CENTRAL BRITISH COLUMBIA, CANADA

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Purpose: Safe and secure national rail networks in Canada are essential for exporting natural resources (e.g., coal, oil, grain, potash, forest products) to deep-water marine terminals, and for transporting goods entering continental North America from global markets. Unfortunately, railway infrastructure and operations across the country are confined to transportation corridors where steep terrain is highly susceptible to landslide activity. Our case study focuses on the North Slide which has posed a hazard to the national railway transportation corridor traversing the Thompson River valley, in south-central British Columbia since 1880. This 1 km2 slow-moving translational-rotational landslide is an ideal field laboratory for testing and evaluating novel landslide monitoring and evaluation techniques as part of International Programme on Landslides Project 202. To evaluate their relative spatial and temporal accuracy and precision, we directly compare deformation measurements calculated from repeat surveys using several commonly used land-measurement techniques.

Methods: Ground-based Real Time Kinematic (RTK) Global Positioning System (GPS), Unmanned Aerial Vehicle (UAV), and satellite-based Interferometric Synthetic Aperture Radar (InSAR) surveys were undertaken over three years (2020-2023). RTK-GPS measurements were collected manually at fourteen ground control points (GCPs) established across the landslide in stable and active zones. A time-series of displacement at each GCP was created from repeat at roughly four-month intervals. Optical imagery with an 80% overlap was collected during periodic UAV surveys, then processed using commercial Structure from Motion software to create a multi-temporal dataset of elevation point clouds, digital surface models (DSMs), and orthomosaic aerial photos. Wide-area horizontal deformation vectors across both active and stable sections of the landslide were derived by digital image correlation techniques applied to the hill-shaded DSMs generated from UAV flights. Vertical deformation was estimated using a simple DSM difference technique. InSAR measurements were collected with a nominal 12-day re-visit frequency, and a 3 m pixel resolution. A multi-temporal network of unwrapped interferograms was generated using a semi-automated InSAR processing system. A dense time-series of line-of-site deformation from a subset network of multi-looked interferograms was recovered by small baseline subset processing.

Results: Time-series displacement measurements of all three measurement techniques are first compared in a point-wise fashion at each GCP location. An accurate basis of comparison is ensured by projecting RTK-GPS and UAV deformation measurements into the InSAR line-of-sight vector. This process provides a temporal basis for comparison, although the number of points of comparison is limited by flight operations, data storage, and processing. Resampling high-resolution UAV deformation measurements to low resolution satellite InSAR measurements allows a wide-area comparison of >20,000 separate points across stable and active zones. Good agreement is typically shown between the UAV and InSAR measurement, although the error between the two appears to scale proportionally to the magnitude of the deformation.

Conclusions: Multi-platform geospatial monitoring of unstable slopes and infrastructure is a cost-effective hazard management practice. This approach provides foundational geoscience information for robust mitigation, adaptation, and other disaster risk reduction measures to maintain resilience and accessibility of critical transportation infrastructure, while also protecting the natural environment, community stakeholders, and Canadian economy.

INTEGRATED REAL-TIME EMERGENCY MONITORING DURING LANDSLIDE RECOVERY OPERATIONS THROUGH COMBINED USE OF INTERFEROMETRIC RADAR AND TOTAL STATIONS

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Purpose: Present paper aims to provide an overview of an emergency monitoring project carried out in February 2020 after a landfill collapse caused two casualties, spreading also on the motorway that runs alongside the refuse site occupying an area of approximately 30 meters-wide and 15 meters-long area of the motorway, reaching a height of four meters. Emergency services, intervened immediately to perform rescue operations and restore traffic circulation, were called to perform their duties in precarious conditions, thus requiring an alerting system capable of detecting any additional movement and providing timely, automatically generated alarms.

Methods: Due to the challenging environment InfoTOP, engineering partner of the public company in charge of managing the motorway, was required to setup an entirely remote monitoring system, to be installed within 400-800 meters from the landslide and capable of a 24/7 real-time data processing with remote data transfer and automatic generation of SMS and email alerts in case of threshold exceedances. To comply with these requirements, InfoTOP opted for the deployment of an integrated monitoring solution combining two total stations with one interferometric radar. The total stations, model Leica Nova TS60 from Leica Geosystems, part of Hexagon, performed three-dimensional measurements of more than 100 prisms installed in the area. Displacement data were managed by Leica GeoMoS software, installed on a virtual cloud infrastructure. The interferometric radar, model HYDRA-G from IDS GeoRadar, part of Hexagon, granted continuous remote monitoring of thousands of points within the danger zone, providing sub-millimetric displacement information, updated every 30 seconds, along the radar Line of Sight (LoS) without the need of any reflector. Data were processed by Guardian software for visualization and management of the automatic alarm generation features.

Results: Concurrent deployment of total stations and interferometric radar allowed to fully exploit the strengths of each technology and at the same time overcome each own relevant limitations: the radar provided real-time displacement information on the whole target area, with 0.1-millimeter accuracy along its LoS, while the two Total Stations covered the areas not detected by the radar, measuring the three-dimensional movement of fewer points according to the available reflectors. These thorough and complemented sets of data were conveyed into GeoMoS software acting as single source of information for both InfoTOP and their geology partners for ease of reference and action. Thanks to this articulated, yet user-friendly and reliable setup, rescue corps were allowed to carry out all the necessary actions with the confidence that any additional movement of the unstable area would have been immediately detected and relevant alarms timely notified.

Conclusions: This case study highlights the benefits granted by the integration of different technologies, in terms of both data detail/accuracy and single interface for visualization and interpretation, crucial aspects especially during emergency rescue operations. Combination of optical systems and radars is being more and more exploited in monitoring projects as innovative solution to have a more efficient data management/interpretation, thanks to the single technology supplier, and at the same time lower operators' workload.

EXTRACTION OF LANDSLIDES DUE TO THE 2018 HOKKAIDO EASTEN-IBURI EARTHQUAKE BASED ON MULTI-TEMPORAL LIDAR DATA

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Purpose: Remote sensing is a popular tool for extracting landslides from earthquakes and rainfalls. Optical and Synthetic Aperture Radar (SAR) satellite sensors have frequently been used, because pre- and post-event images covering affected areas are often available. Various change detection or classification techniques have been applied for these images. The change detection techniques usually extract two-dimensional (2D) changes in objects on the Earth's surface. However, the situations of landslides can be expressed more precisely by 3D changes. To carry out 3D change detection, multi-temporal 3D models in the form of digital elevation models (DEMs) are necessary. DEMs are typically represented by a digital surface model (DSM), which includes trees and buildings, and a digital terrain model (DTM), in which those Earth surface objects have been removed. The use of multi-temporal airborne LiDAR (Light Detection and Ranging) data is attempted to extract landslides due to the 2018 Hokkaido Eastern-Iburi, Japan, Earthquake and the results are compared with those from other remote sensing data.

Methods: LiDAR data give the highest accuracy for the surface elevation and very high resolution if the point cloud density is high. This study introduced pre- and post-earthquake LiDAR data to extract landslides in Atsuma Town after the 2018 Hokkaido Eastern-Iburi Earthquake. Numerous landslides occurred in the eastern Iburi area due to this event. By taking the difference in LiDAR DSMs and in LiDAR DTMs acquired at pre- and post-event times, landslides were extracted as the reduction of surface elevations where the grounds were slipped down and the increase of surface elevations where slipped soils were accumulated.

Results: A large number of landslides were extracted in the study areas by taking the DSMs and DTMs difference in the mountain slopes. The results were compared with those from aerial optical images [1] by the Geospatial Information Authority of Japan (GSI) and those from satellite Synthetic Aperture Radar (SAR) images [2], and our field investigation data. The extracted landslide areas showed a very good agreement with those from the other remote sensing data. Not only the 2D aerial changes, the LiDAR data could identify the volume of each landslide by the 3D change.

Conclusions: This study introduced airborne LiDAR data to extract landslide areas due to the 2018 Hokkaido Eastern-Iburi Earthquake. By comparing the pre-event and post-event DSMs and DTMs, the areas and volumes of landslides are extracted accurately and the results were validated through the comparison with those from other remote sensing data and field investigation data.

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MULTI-METHOD LONG-TERM ASSESSMENT OF A LANDSLIDE REACTIVATED BY THE EXTREME 2021 FLOOD EVENT IN THE AHR VALLEY (GERMANY)

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Purpose: The extreme 2021 flood event in the Ahr valley (western Germany) caused 134 fatalities, enormous damage and economic loss, and led to severe erosion and sedimentation. Multiple shallow landslides were triggered along the Ahr embankments. Furthermore, several old landslide bodies were undercut. One such landslide in Devonian Schist bedrock is located at a narrow, bended reach of the Ahr, near the town of Müsch. Investigations at this site are relevant to study long-term effects of extreme events and to assess the potential of a valley-blocking landslide reactivation and cascading hazards. The main objectives of this study are to understand the landslide mechanisms and its time-lagged, transient activity after the initial flood and sliding event.

Methods: These objectives are tackled by a multi-method approach: landslide mapping, analysis of pre- and post-event airborne laser scanning (ALS), terrestrial laser scanning (TLS) and UAV data, electrical resistivity tomography (ERT), seismic refraction tomography (SRT), passive seismic monitoring, geotechnical analysis and interviews with local inhabitants.

Results: Results indicate a landslide, 100 m wide and 200 m long with an estimated depth of 15-20 m, leading to an overall landslide volume of approximately 430,000 m^3. Analysis of remote sensing data shows that so far only the frontal part at the Ahr river banks has been active and about 7000 m^3 have been removed by fluvial erosion and landsliding. Movement in the sliding body continued episodically for more than a year after the initial event – even though the summer of 2022 was rather dry. The slope shows clear signs of retrogressive landsliding. Field observations show ongoing activity in February 2023. Continuous UAV and seismic monitoring enabled surface and subsurface change detection in the frontal sliding area. Thousands of signals of rock bridge failures could be detected and located around the perimeter of the unstable mass, with focussed activity at the frontal part.

Conclusions: The combination of geophysical and remote sensing methods allows a profound insight into the mechanisms and present processes of the Müsch landslide. Based on the ongoing landslide surveying, we plan to assess the probability for a reactivation of the whole landslide body, which could trigger cascading hazards affecting a much larger region. An improved monitoring concept will be developed which can be adopted to similar structures in other regions.

A MULTI-SENSOR AND MULTI-VARIABLE SATELLITE OBSERVATION APPROACH FOR INVESTIGATING LANDSLIDE LIFE CYCLE AND THE CONTROLLING ROLE IN THEIR MECHANISM OF METEOROLOGICAL AND HUMAN FACTORS: MARCH 2019 HOSEYNABAD-E KALPUSH DISASTER IN IRAN

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Purpose: Dam reservoirs have been widely reported for influencing the stability mechanisms of the surrounding slopes and intensifying landslide hazards. The combined destabilization effect of reservoir water level changes and extreme precipitation events due to climate change has been poorly investigated. In-situ monitoring systems over landslide-prone slopes are often unavailable, challenging landslide hazard assessment in many regions. A multi-scale and multi-sensor satellite remote sensing approach combined with advanced statistical methods is proposed to investigate the landslide life cycle and the role of meteorological and human factors leading to a catastrophic landslide failure in March-April 2019 in Semnan province of Iran. The landslide failure occurred following an exceptional precipitation period on the adjacent slope of a nearby reservoir built in early 2013.

Methods: PlanetScope images (10.2018-05.2019) are processed using Digital Image Correlation with Fast Fourier Transform (FFT) approach to assess the main failure. Ascending and descending orbit ENVISAT (07.2003-09.2010) and Sentinel-1 (10.2014-12.2021) data are processed using Small Baseline Subset SAR interferometric technique to derive pre- and post-failure ground deformations. The Climate Hazards Group InfraRed Precipitation with Station data is used to obtain monthly cumulative precipitation. The reservoir water level was derived utilizing a GIS-based approach using Landsat-8 (04.2013-08.2016), PlanetScope (08.2016-12.2021) data and a digital elevation model. Pre- and post-failure ground displacement observations are first decomposed using principal component analysis (PCA) to derive main kinematic patterns. Hierarchical clustering is applied to the final cumulative map and digital elevation model to partition the landslide body based on kinematics. The average time series and the standard deviation are derived for each cluster and decomposed into main trends and seasonality using optimized piecewise linear regression. Finally, seasonality and changes in trends are correlated to precipitation and reservoir water level values.

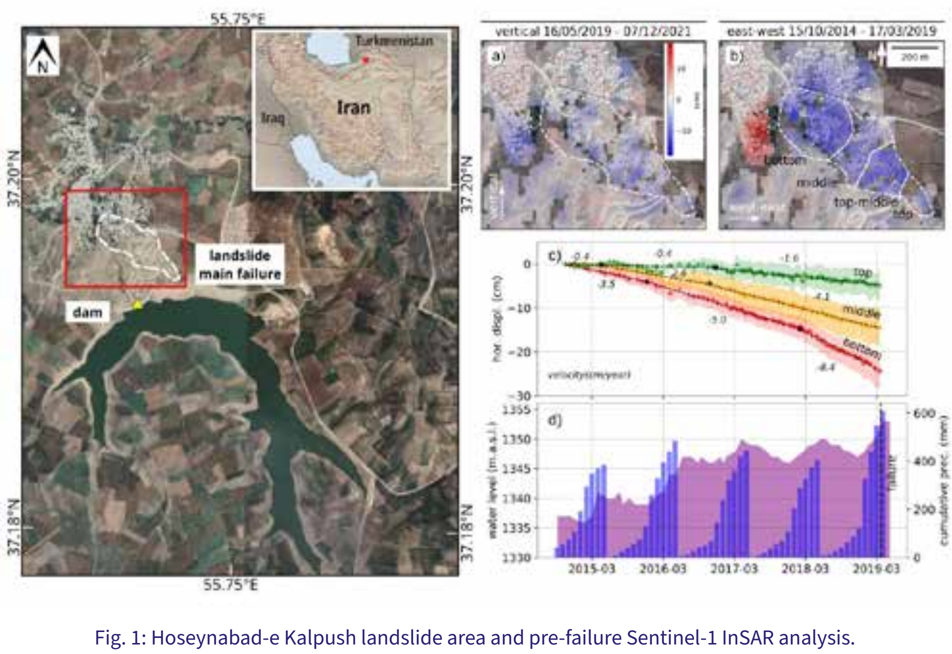

Fig. 1: Hoseynabad-e Kalpush landslide area and pre-failure Sentinel-1 InSAR analysis.

Results: First destabilization trend of a horizontal rate of 3.5 cm/year was observed in the lower sector starting from October 2014. Between 2016 and 2018, the instability of the toe intensified to 8.4 cm/year and propagated upslope as the impoundment of the reservoir continued. In spring 2019, 90% of the annual precipitation average fell in only three months, increasing the reservoir water level to its maximum ever registered value. The slowly moving failure culminated in the main landslide failure at the end of March, reaching a maximum cumulative horizontal displacement of more than 40 m on the upper part of the landslide until May 2019. In the aftermath, the landslide was still active with trends in displacement rate comparable to the pre-failure phase, which decreased until a final stabilization in the second half of 2021.

Conclusions: Influenced by the impoundment of a nearby reservoir, a previously relict landslide was reactivated following a retrogressive destabilization mechanism. The almost five years of landslide creep degraded the slope's geomechanical properties. The exceptional precipitation in the spring of 2019 increased in a short time the pore-water pressure within the slope triggering a deep-seated landslide rupture.

SESSION 5.3

TOWARDS A HOLISTIC UNDERSTANDING OF LANDSLIDE-INDUCED DISASTER CASCADES IN THE HIMALAYAS

PROBABILISTIC MODELING OF LANDSLIDE HAZARDS IN THE NORTH-WEST HIMALAYAS: A CASE STUDY OF MALLI BAZAR LANDSLIDE

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Purpose: Landslides are one of the most catastrophic natural hazards which occur very frequently in the Himalayan region of India, particularly in the North-West Himalayas. High-rise mountains, steep slopes, fragile geology, prolonged rainfall events, and regular seismic activity make the region more susceptible to landslides. Also, the changing climate is leading to fluctuations in temperature and precipitation patterns in the region, impacting the frequency and severity of landslides. Consequently, forecasting and mitigating landslide hazards have become more challenging. On July 28, 2022, a landslide occurred in Malli Bazar of Dharchula town, Uttarakhand, India, blocking the Kailash-Mansarovar National Highway and damaging residential complexes in the surrounding area. The objective of this study includes investigating the probable causes of the Malli Bazar landslide and determining the probability of possible future failures while recommending effective mitigation strategies using a comprehensive approach.

Methods: With advancements in numerical modeling, probabilistic models are becoming popular for slope stability analysis, enabling uncertainties to be included in the analysis. Furthermore, back analysis has been found to be an effective method for estimating strength parameters at the time of failure, improving the accuracy and reliability of numerical modeling. Hence, this investigation utilizes the outcomes of the field survey and back analysis to ascertain the likelihood of forthcoming failures. The probabilistic slope stability analysis of the Malli Bazar landslide was performed using Slide 2D (Rocscience) software with Spencer's and Bishop's simplified methods. The model was simulated using the Latin hypercube sampling method under static and dynamic conditions while considering the dry and saturated scenarios.

Results: The field investigation indicates that prolonged heavy rainfall has saturated the loose debris, reducing intergranular friction and making it cohesionless. The Electrical Resistivity Tomography (ERT) survey revealed a thick layer of loose debris (>35m) and groundwater at a depth of 30-35m. The SLIDE 2D software, based on the Limit Equilibrium Method, was employed for numerical modeling. The analysis shows that the slope is stable under dry conditions, with a factor of safety value of 1.17 and a probability of failure of 46.8%. However, under saturated conditions, the slope is highly susceptible to failure, with a probability of failure of 81.3% and a safety factor value of 0.91. In addition, the numerical simulation incorporated the effects of seismic activity by considering dynamic conditions. The results indicated that the slope's likelihood of failure is very high, with a probability of failure of 93.7% and a safety factor of 0.83.

Conclusions: The results of numerical modeling and field investigation indicate that the current slope has a high probability of failure during heavy rainfall. Therefore, it is necessary to implement adequate mitigation measures on this slope to prevent future catastrophic impacts on locals. Based on the slope's current conditions, several rows of micro piles at different levels are recommended to arrest land movement. Furthermore, rockfall barriers must be installed to catch loose boulders, and a gabion wall at the toe of the slope should be constructed to prevent further toe movement.

SEISMIC MONITORING OF LANDSLIDE IN THE HIMALAYAS: A CRITICAL TOOL FOR DISASTER PREVENTION

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Purpose: Some of the youngest mountains on Earth are the beautiful Himalayas, with towering peaks and spectacular valleys. Their relative youth, however, also implies that they are ever-evolving and adapting to new circumstances as natural processes form and remodel their landscapes. Earthquakes, floods, and landslides are commonplace because of the region's rapid expansion and the Mountains' unusual geographical position. Slope failures and landslides, which endanger the lives and livelihoods of individuals who live in this stunning area, have been caused by these unfortunate events. After going through many past research and literature, it has been identified that the best way to close effective solutions for landslides triggered by extreme events is, Seismic Monitoring of the Himalayas. Debris flow, avalanches, rock falls, lahars, pyroclastic flows, and outburst floods are all examples of surficial mass movements that pose a severe threat to many landsides across the world. The science of landslide monitoring would be advanced, and hazards mitigated by a better understanding of these processes, a database of their spatiotemporal occurrence, and the detection, tracking, and characterization of these events. Seismic and acoustic methods show promise for achieving these objectives. Numerous surficial mass movements create visible seismic and acoustic signals, and several landslides are already monitored. Several advances have been conducted in our ability to interpret, predict, and quantify seismic and infrasonic signals caused by changes in surficial mass. Substantial advancements have been achieved in our ability to interpret, model, and extract quantitative information from seismic and infrasonic signals caused by changes in the surficial mass.

Methods: We have 18 seismometer sensor arrays installed in the Himalayas. Based on our sensor-covered area, we studied the Chamoli Ice-rock avalanche disaster. Our methodology is very straightforward; we have set up the real-time data analysis observatory. First, real-time data have been filtered in an effective frequency range, and then filter signals have been processed through some best time-frequency analysis techniques.

Results: Four distinct phases of the Chamoli event are revealed by the time-frequency analysis, with the ice-rock fall contributing the highest dominant frequency (16-18) Hz and the earthquake at the nucleation phase before the event accounting for the lowest frequency (2-5 Hz). After the detachment phase, the surface wave's speed is estimated to increase to around 3 km/s. We computed the time difference based on different stations to evaluate the seismic network's early warning potential. We devised a warning period of 12 and 18 minutes at distances of 13 Km and 19.7 Km from the source, respectively.

Conclusions: Our study reveals that if any seismic monitoring system has been installed for such events in the Himalayas, it can save many lives in the future. Due to the mountainous terrain and the numerous hydropower projects in the Himalayas, scientists should work to increase the current network's sensing capabilities to provide more time for disaster preparation and mitigation.

TOWARDS ESTABLISHING AN OPTIMAL REGIONAL RAINFALL THRESHOLDS FOR LANDSLIDE OCCURRENCE IN HIMACHAL PRADESH, INDIA: A COMPARATIVE STUDY OF METHODS AND DATASETS

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Purpose: Himachal Pradesh (HP), India is one of the North-Western Himalayan states in which monsoon precipitation is the primary cause of the majority of landslides. Because approximately two-thirds of the annual precipitation falls during the monsoon and the highest number of landslide incidents also occur during the monsoon. Thus, it becomes vital to investigate the connection between these two, demanding the establishment of an empirical relationship. In addition to developing a regional scale rainfall threshold equation for the initiation of landslides in the state, the purpose of this study is to compare different methodologies and datasets to determine the optimal combination for conducting such research in data-scarce hilly terrains like HP.

Methods: In the present study, the authors decided to incorporate both intensity-duration (ID) and event-duration (ED) approaches for threshold calculation, and to quantitatively evaluate the outcomes of both methods on different datasets, namely satellite data {Tropical Rainfall Measuring Mission (TRMM)} and station data {India Meteorological Department (IMD)}. To determine the ideal combination of a method and data set, a quantitative validation analysis of the findings of several combinations has been done.

Results: The rigorous analysis of 209 landslide data from 2007 to 2017 yielded multiple empirical threshold equations by combining different methods and datasets. Finally, validation of the threshold equations was performed using a validation dataset (15% of the total data). To gain a deeper understanding of the performance of the threshold models, a detailed quantitative study was conducted utilising statistical attributes generated with a confusion matrix. Considering these characteristics, the authors determined that the combination of ED method and TRMM dataset with an efficiency (Ef) of 0.783 and a likelihood ratio (LR) of 4.595 was superior to all other combinations.

Conclusions: Numerous studies have attempted to establish a relationship between landslide occurrences and rainfall characteristics in various sections of the Indian Himalayas (i.e., for Uttarakhand state, Northern parts of West Bengal state, and North-Eastern states of India), but despite its national significance in the tourism industry, Himachal Pradesh remains unattended and understudied in terms of empirical relationships. In the state of HP, high-resolution rainfall datasets and an updated landslide inventory are unavailable. Consequently, this study investigates the aforementioned issues and proposes a quantitative approach for comparing multiple methodologies and datasets simultaneously for the optimal rainfall threshold definition in order to determine which of them is the most effective combination for identifying the minimum rainfall conditions that could lead to landslide activities in the state. To arrive at the optimal threshold equation, the authors conducted extensive and quantitative validation studies and established that a combination of ED and TRMM would be the most effective method for determining landslide thresholds in the state. The authors hope that this performance-based strategy to combining datasets and methods will provide a new way for researchers to select the optimal dataset and method for computing rainfall thresholds for landslides in the majority of data-scarce locations of the world, such as HP.

AN INTEGRATED FRAMEWORK TO ASSESS THE IMPACT OF EXTREME PRECIPITATION-INDUCED CASCADING HAZARDS IN THE HIMALAYAS

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Purpose: The Himalayas are highly vulnerable to climate change impacts, and in recent years an increase in the frequency of natural hazards has been witnessed. The threat of natural hazards exacerbates when events occur in cascading nature (the primary hazard triggers the secondary hazard). The prominent cascading hazards in the Himalayas are landslides, flash floods, debris flows, and hydro-geomorphological hazards. The effects of climate change and anthropogenic activity, such as increased precipitation, rising temperature, deforestation, and unplanned construction, will likely exacerbate these cascading hazards in the future. Therefore, it is crucial to have an integrated framework to assess the impact of these cascading hazards, which will help to have appropriate risk reduction and management strategies to reduce the region's vulnerability and minimize the impact of cascading hazards.

Methods: This proposed novel framework simulates the process of interaction between extreme precipitation and hill slopes, which can induce landslides. It then models the two-phase flow resulting from the runoff generated by the precipitation mixing with the landslide deposits, ultimately resulting in debris runout. To account for the uncertainty in data, the framework incorporates four sources of precipitation data, including gridded observation datasets, reanalysis data, satellite data, and numerical weather prediction models. While accounting for the inherent uncertainty in precipitation data, this approach aims to provide a more comprehensive understanding of the complex dynamics contributing to cascading hazards. Using the precipitation dataset with the least uncertainty, the landslides are analyzed and validated using a polygon-based inventory. The aerial extents of landslides are cross verified using the inventory. Using empirical area-volume relationships, landslide volumes are estimated, which is then used to validate the model-derived values.

Results: The approach estimates the volume of sediments generated from the hillslopes and predicts the volume of sediments reaching the river junctions during extreme events. In addition, preliminary processes of geohazards' cascading nature, i.e., the conversion of landslides to debris flows, are numerically simulated.

Conclusions: This study proposes an approach to numerically simulate extreme-precipitation-induced cascading hazards starting from rainfall-induced landslides, runoff generated debris flows and the transport of huge volumes of sediments to the river. The framework is validated using the 2013 North India Floods, an extreme-precipitation event that triggered more than 4000 landslides and debris flows.

SEASONALITY INFLUENCE ON CASCADING PROCESSES RESULTING FROM AVALANCHES MADE OF MULTIPLE COMPONENTS (ROCK, ICE, SNOW, WATER)

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Purpose: Multicomponent avalanches are events where more than one type of material is involved (i.e. rock, ice, water, snow). These events tend to propagate to larger runout distances than single phase flows, partly due to their ability to turn into a cascade of events over the course of their flow. An example of cascading event is the rock ice avalanche which occurred in Chamoli, India in 2021. There, 27 Mio cubic meters of rocks and ice collapsed from Ronti Peak, eventually turning in a water dominated flow that ran out over almost 20 km. When back-calculating this event using a multiphase gravitational flow model, we note that two elements strongly impact the ability of the flow to turn into a cascade of events: 1) the water content of the flow, 2) the amount of material in the flow and its overall composition The water content of the flow depends on the release composition, how much water is present it there, but also how much ice and snow, as these materials melt due to shear work as the flow propagates. Water content also depends on materials that can be entrained on the way, the presence of water or water saturated sediments, the presence of snow or ice which and how much of these can be entrained and melted.

Methods: We modelled several multicomponent avalanche scenarios varying the amount of snow present on the release or on the path of the avalanche, mimicking some seasonality, with a “summer”, snow poor scenario and a “winter”, snow rich scenario. To do this, we used a new module of the RAMMS software designed to model avalanches composed of more than one kind of material.

Results: Our results show that for events such as Chamoli, the runout of the avalanche is lengthened by several km when a snow cover is involved in the process. This changes drastically the hazard assessment for the areas concerned by strong seasonal variations. This comes from the fact that a snow cover not only provides mass into the descending flow but also material which can potentially melt and increase the water content and subsequent flow regime of the event. In regions that are subjected to strong precipitations such as monsoon, such variability might also have to be considered. Indeed, extreme precipitations have been suggested to favour landslides triggering, but one also must keep in mind that the ground material that could be entrained will also contain a higher amount of water, which, again, could increase the runout of the flow.

Conclusions: In summary we show the strong effect of a snow cover and highly water saturated material on the runout and general evolution of a multiphase event and discuss the implication regarding hazard mitigation in areas concerned by a strong seasonality.

EXPERIMENTAL STUDY ON THE FAILURE MECHANISM OF MORAINE DAMS WITH DIFFERENT COMPACTNESS COMPOSITION UNDER SURGE ACTION

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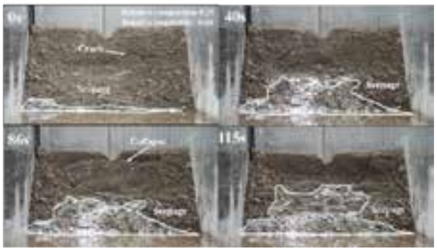
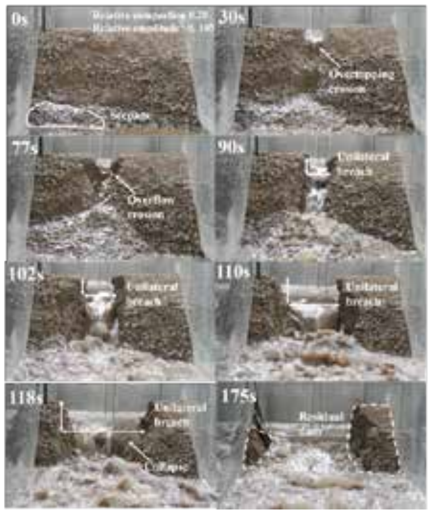
Purpose: In recent decades, global warming, the rapid melting of glaciers and the occurrence of some extreme rainfall weather have catalyzed the formation of moraine lakes in concave terrain with certain conditions. Currently, the size and number of moraine dams and glacial lake systems are significantly increasing under the influence of climate change, and under the right trigger conditions, these natural moraine dams can break, producing catastrophic glacial lake outburst floods (GLOFs). A large number of moraine dams, both broken and intact, show evidence of inundation by surge waves. The purpose of this study is to investigate the effect of compaction and surge wave amplitude on moraine dam failure modes, which can provide valuable insights for disaster prevention measures in high-altitude areas prone to glacial lake failure.

Methods: The study employed a range of methods, including analysis of field sampling data, indoor testing, and analysis of historical events. Moraine dam models were created with varying degrees of relative compactness, obtained through natural accumulation and artificial compaction. These models were subjected to impacts of ice and rock mixtures in carefully selected volume proportions, ensuring that the generated surge waves were neither too large nor too small. To record the impact force and deformation characteristics of the dam and breach, 3D laser scans, pore water pressure sensors, and pulsating water pressure sensors were utilized.

Results: The results showed that the destabilization modes of moraine dams can be controlled by surge wave amplitudes and the degree of dam compactness. Under the specific particle size distribution condition of this experiment, the four destabilization modes identified were overall breach, overflow erosion, seepage, and combined erosion. For instance, significant overflow erosion occurs when the relative compaction of the moraine dam is 0.35 and the relative wave height is 0.105, while significant seepage damage occurs mainly when the relative compaction is 0.25 and the relative wave height is only 0.04. When the relative compaction is 0.28 and the relative wave height is 0.064, both overflow erosion and seepage occur, leading to partial sliding of the downstream part of the dam slope and gullies on the slope surface. When the relative compaction is 0.28 and the relative wave height is 0.105, the moraine dam begins to break directly from the notch, accompanied by collapse on both sides of the dam.





Figs can demonstrate some of the experimental phenomena.

Conclusions: In conclusion, this study emphasizes the importance of considering the compaction and surge wave amplitude effects on moraine dam failure modes, in addition to grain size distribution, for disaster prevention measures in high-altitude areas. The findings can be used as a basis for developing more effective strategies for preventing glacial lake failure disasters.

INVESTIGATING VERTICAL HETEROGENEITY OF SOIL-ROCK MIXTURES AND UNSATURATED SHEAR STRENGTH OF LANDSLIDE DEBRIS IN THE HIMALAYAS

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Purpose: Rainfall-induced slope failures over soil-rock mixtures are common in mountainous regions. The mountainous debris primarily consists of fragmented rocks (gravels/boulders/cobbles) and residual soil matrix around the rocks. They exhibit a broad spectrum of grain size distribution, ranging from several meters of rocks to plastic fines as small as a few microns. As a result of the diverse distribution of grain sizes (GSD), the characteristics of mountainous debris exhibit notable variations, making it a difficult endeavor to assess its geomechanical characteristics and behavior. The properties of mountainous debris vary significantly with depth because of variation in grain sizes of debris matrix and weathering. The characteristics of residual debris matrix often cause instability of slopes during infiltration, especially in Indian Himalayas where severe rainfall events are common. The variability of debris properties causes difficulty in performing slope stability analyses for disaster mitigation. As such, it is crucial to characterize the debris properties at different depths. For this purpose, index properties, soil–water characteristic curve and unsaturated shear strength tests were carried out on debris samples sampled from different debris flow sites in Uttarakhand, India.

Methods: To obtain a grain size distribution and to characterize the mountainous debris, a methodology that involves integrating three techniques is employed. To analyze particles within the size range of 0.075 mm to 100 mm, sieve analysis is employed. Gravelometer is utilized for particles ranging from 100mm to 300mm, and for rocks larger than 300 mm, the pebble count and survey tape method is employed. To determine the depth-related variations, the analysis is conducted at three different depths: 50 cm, 100 cm, and 150 cm. Afterwards, lab experiments are conducted using samples from various depths to estimate the index properties, unsaturated shear strength, and soil water characteristic curve. In this study, particular emphasis is given to computing the impact of grain size on the unsaturated shear strength of the soil.

Results: We observed that the mountainous debris is very rich in humus and contains a wide range of grain sizes. The shear strength of debris deposits are mainly because of frictional resistance between the particles as the cohesion is less between the particles. The depth related variation is very uncertain in mountainous soil as the thickness of debris varies significantly from place to place. We observed that in the case of shallow slope failure the soil matrix plays an important role as the failure is most likely through the soil matrix but in the case of debris flow rocks or gravels play an important role as they dictate the energy and behavior of the flow.

Conclusions: This study investigated the vertical heterogeneity of soil-rock mixtures and unsaturated shear strength of landslide debris in the Himalayas. It is found that these debris pose sensitivity to unsaturated characteristics and their behavior should be analyzed. The results of this study have implications in landslide and debris flow risk assessments in the Himalayas.

SESSION 4.2

SPATIAL LANDSLIDE ASSESSMENTS AND BEYOND: NEW CHALLENGES IN MAPPING, MODELLING, VALIDATION AND SCENARIO BUILDING (part III)

INFLUENCE OF INDISTURBED PARTS OF SLOPE AND THE ORIENTATION OF BEDDING STRATA TO LANDSLIDE SUSCEPTIBILITY ASSESSMENT

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Purpose: In the last decades, landslide susceptibility and hazard assessment have drawn attention of many researchers around the World. A certain number of parameters are suggested to be responsible to explain the triggering mechanism of landslides. It is important to note that some data types and methods of assessement are site-specific and could not be directly applied to different locations. During the preparation of a landslide inventory map (from field investigation) in Western Polish Carpathians have been observed significant difference of landslides density. The aim of this study is to understand the reason for this difference in landslide density and produce a landslide susceptibility map of the study area.

Methods: To evaluate the contribution of conditioning factors to landslides of the study area the analysis using a Frequency Ratio (FR) Model and GIS mapping was implemented. This method allowed also to assess the relationship between each of the conditioning factors and their impact on the occurrence of landslides. In order to achieve this goal, two new concepts: seed cells and geological orientations of slopes are introduced. Seed cells are the zones that are considered to represent the undisturbed parts of the slope (conditions before landslide occurs). Seed cells were achieved by adding a buffer zone to the crown and upper boundary of the landslide. Geological orientation of slopes is a new data layer which presents relationship between slope angle and strike and dip direction of strata below a slope surface.

Results: FR values was calculated using both: landslides and seed sells. They were used to compare and choose better result of landslide susceptibility map of the study area. The results of the analysis have been validated by calculating the Area Under a Curve (AUC), which shows an accuracy of prediction rate curve of 77.30%. This value is the highest results for the Landslide Susceptibility Index (LSI) obtained using a combination of frequency factors calculated by the use of both: landslides and seed cells (buffers). The result shows that lithology, slope angle, distance from tectonic structures are the most important factors generating landslides and causing difference in landslide density in the study area.

Conclusions: The best result of landslide susceptibility map was obtained as a result of combining the FR values of the triggering factors which was calculated by the use of landslides and seed cells. In addition, it seems to be very important to include the angle of dip of inclined strata in the calculation of landslide susceptibility.

AN INTEGRATION OF THE FRACTAL METHOD AND THE STATISTICAL INDEX METHOD FOR MAPPING LANDSLIDE SUSCEPTIBILITY IN MUONG KHOA COMMUNE, SON LA PROVINCE, VIETNAM

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Purpose: Appropriate land use planning and the sustainable development of residential communities play a crucial role in the development of mountainous provinces in Vietnam. Because these regions are especially prone to natural disasters, including landslides, landslide studies can provide valuable data for determining the revolution of the landslide process and assessing landslide risk. This study was conducted to assess landslide susceptibility in Muong Khoa commune, Son La province, Vietnam. To produce landslide susceptibility zonation (LSZ) maps, eight causative factors, including elevation, slope aspect, slope, distance to roads, distance to drainage, distance to faults, distance to geological boundaries, and land use, were considered.

Methods: The Statistical Index method (SI) and an integration (FSI) of the Fractal method and Statistical Index method were employed in this study to evaluate the susceptibility of the study area to landslides.

Results: The spatial relationships between the distribution of past landslides and landslide causative factors were evaluated with the use of eight causative factor maps. Using SI and FSI models, two landslide susceptibility zonation maps were produced in ArcGIS. The study territory was categorized into five susceptibility zones based on the LSZ map: very low, low, moderate, high, and very high. The percentage area of susceptibility zones predicted by the SI model is 10.11, 18.49, 29.71, 28.59, and 13.10%, respectively. Meanwhile, the susceptibility map generated by the FSI model divided the study area into zones with corresponding area proportions of 18.92, 18.71, 20.01, 22.94, and 19.42%. Using the ROC method, the prediction performance of the two models was determined to be AUC = 71.18% (SI model) and AUC = 75.18% (FSI model).

Conclusions: The AUC > 70% indicated that the models established a good relationship between the spatial distribution of past landslides and causative factors. In addition, the two models accurately predicted the occurrence of landslides in the study area. The FSI model has improved prediction performance by identifying the role of each factor in the landslide occurrences in the study area. Therefore, this study's methods and outcomes may be effectively utilized in other regions and contribute to Vietnam's landslide prevention strategy.

THREE-DIMENSIONAL SLOPE STABILITY ANALYSIS BASED ON LIMIT EQUILIBRIUM THEORY FOR A LARGE AREA

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Purpose: Numerical simulations of landslides have been highly developed and became one of the important tools for landslide risk assessment. However, in the analysis over a wide area, many of them are based on statistical models or simple physics-based models. Considering future improvements in computational techniques and capabilities, it is important to consider the application of advanced physics-based models. In particular, studying in detail the applicability of the 3D Limit Equilibrium Method(LEM) to actual problems is important from the viewpoint of practical use of the numerical simulation in landslide risk assessment.

Methods: Based on the background mentioned above, this study aims to investigate the performance of the 3D LEM-based slope stability analysis methods by simulating actual landslide events occurred in wide area. Hovland's method, 3D simplified Bishop's method, 3D simplified Janbu's method, and 3D Spencer's method are employed, and the performances of these methods are examined. A mountainous region affected by 2019 Typhoon Hagibis is selected as a target area, and the digital elevation model provided by the Geospatial Information Authority of Japan is used to represent the actual terrain. Regarding the groundwater, fully saturated condition is assumed because of a lack of the information.

Results: A series of slope stability analyses on a simple slope with an ellipsoidal slip surface was performed. The calculated factors of safety were larger in the order of Hovland's method, 3D simplified Janbu's method, 3D Spencer's method, and 3D simplified Bishop's method (Figure 1). 3D Spencer's method was found to be very unstable compared to other methods. In the analysis over a wide area, it is difficult to properly determine whether convergence to the correct solution at all locations. Therefore, we decided not to use the 3D Spencer's method for the wide-area slope stability analysis.

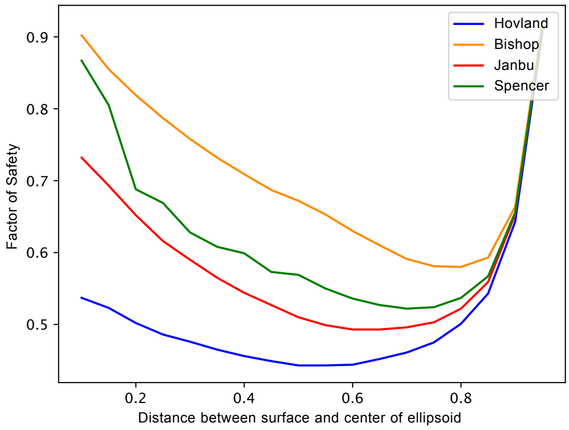

Fig. 1: Analysis results on a simple slope.

According to the results of analyses using the actual terrain data, Hovland's method extracted larger unstable areas compared to the other methods (Figure 2). We also compared the extracted unstable areas with the observed distribution map of the actual landslides. As a result, all the methods drew similar ROC curves (Figure 3). This indicates that all methods can output similar distribution by changing the threshold of the factor of safety. Therefore, there is a possibility that Hovland's method, which has the lowest computational cost, can output similar results obtained by other methods by only changing the threshold. This is important from the viewpoint of practical use of 3D LEM because slope stability analysis over a wide area generally demands high computation costs.

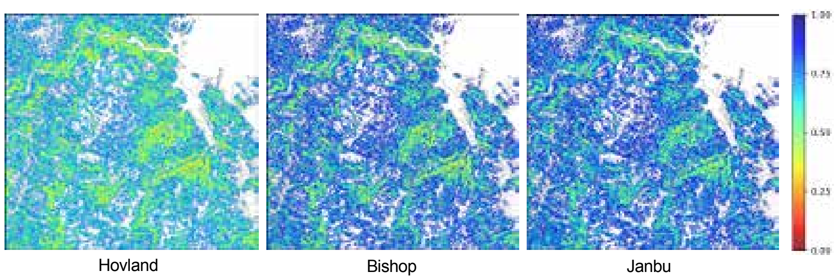

Fig. 2: Mapping of factor of safety

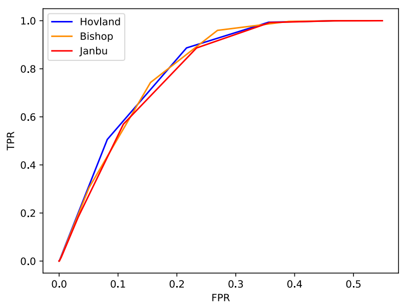

Fig. 3: Comparison of ROC curves

Conclusions: The results of slope stability analyses suggested that a simplifier method may be able to approximately reproduce results obtained by methods that need high computational cost by changing the threshold of the factor of safety. However, the calculation conditions considered in this study do not exactly match the actual conditions. The conclusion mentioned above is hence limited to the range of computational conditions considered in this study, and further research is needed.

LANDSLIDE DAMMING FORECASTING: A TOOL FOR RISK MANAGEMENT AND LAND USE PLANNING

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Human activities (such as industry and agriculture) are often concentrated on the valley floor and near rivers. Landslide dams are natural hazards that can cause significant damage and risk to upstream and downstream communities, infrastructure and ecosystems. The rapid evaluation of dam stability during an emergency is essential for mitigating the consequences. However, performing a reliable risk assessment can prove challenging given the limited time available. Therefore, hazard susceptibility maps are an essential tool for risk management and can be used to identify areas where preventive measures are required.

The study presents a new methodology to assess the hazard susceptibility of landslide dams using easily and worldwide available digital data and geographic information system (GIS) techniques. The proposed methodology combines morphometrical information from a landslide ad an involved river valley to determine the potential for landslide dam formation in that given area based on a correlation of morphometric parameters described by a morphological index, the Morphological Obstruction Index (MOI). The combination of this indicator with the analysis of landslides distribution allows to assess the river obstruction through two main mechanisms, the reactivation of mapped landslides and the formation of new landslides.

The methodology was tested in a test area, the Arno River basin in Italy, a region known for frequent landslides and landslide dams. The obtained maps were validated using historical data of past landslide dam events, and the results showed a good correlation between the predicted susceptibility and the actual occurrence of landslide dams.

In conclusion, the proposed GIS-based methodology provides a robust and effective approach for assessing the damming susceptibility. The methodology can be adapted and applied to other regions prone to landslide damming, providing valuable information for risk management and land use planning. The results of the study have important implications for risk management and land use planning in areas prone to landslide damming. The maps can be used to identify high-risk areas where infrastructure reinforcement and preventive measures, such as early warning systems or emergency planning, are needed. The maps can also inform land use planning by identifying areas where development should be restricted or prohibited due to the high risk of landslide dam formation.

SUSCEPTIBILITY ASSESSMENT WITH QGIS. SZ-PLUGIN DOES IT ALL?

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Purpose: Anyone who has carried out a susceptibility analysis at least once, can confirm how many tools, software or self-made scripts are necessary to compile a valuable susceptibility map: one tool to pre-process the data, one tool to analyze the data and one tool to validate the results. Numerous tools and software are in fact available for susceptibility analysis. Some of them are focused on spatial susceptibility or susceptibility zoning and are developed on both proprietary and open-source Geographical Information Systems, such as: GRASS (r.landslide), ArcGIS (ArcSDM and Toolboxes), R (LAND-SE and RSAGA). In this work we present a new, unified system to perform the whole modeling procedure called Susceptibility Zoning plugin (SZ-plugin) for QGIS. QGIS is probably the most common open-source geographical information system. Its success is related to an active community of users and developers which make it perfect for our purposes.

Methods: The plugin is a collection of functions wrote in the past few years and organized to be concatenated. Based on open-source technologies the plugin allows the user to pre-process the data, to map the susceptibility, to cross-validate and spatially cross-validate the results, to classify the final index and to evaluate the related uncertainties. Based on a number of classifiers including Weight of Evidence, Frequency Ratio, Logistic Regression, Random Forest, Support Vector Machine, and Decision Tree, the user can calibrate, validate, predict in space and time the susceptibility of a specific event category by using a number of cross-validation methods: single validation, k-fold cross-validation and spatial cross-validation. The evaluation of the prediction capacity of the susceptibility zonation is based on the Area Under the Receiving Operating Characteristic curves. Despite the fact that the SZ-plugin has been developed for landslide susceptibility evaluation, there are no limits to the possible applications. The entire analysis is based on vector (table) data format which give the possibility to interpret several mapping units such as: square grid cells (equivalent to pixels), slope units, Unique Condition Units, any other irregular or regular polygonal shapes.

Results: The SZ-plugin has been tested and applied several times in different study areas, some of which will be presented in this work. The plugin has demonstrated stability, versatility and computational rapidity. As confirmed by first time users the Graphical Interface is extremely user friendly and intuitive.

Conclusions: How many tools or software are necessary to conduct a susceptibility assessment? The SZ-plugin has been designed to simplify and automatize as much as possible the evaluation, validation and classification of susceptibility in space and time, collecting well consolidated techniques in one single tool. Further improvements will be focused on the implementation of novel quantitative methods for susceptibility calculation. The code repository, further versions and upgrades are freely available on GitHub: https://github.com/CNR-IRPI-Padova/SZ.

IDENTIFYING THE FUNDAMENTAL MAPPING UNIT FOR SHALLOW LANDSLIDE SUSCEPTIBILITY MAPPING IN A TROPICAL REGION - CASE STUDY IN THE WESTERN GHATS, INDIA

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Purpose: Tropical region, sandwiched between the Tropic of Cancer and Capricorn, is characterized by high precipitation, which is usually more than twice the amount of the driest year. One such region is the Western Ghats in India, which is characterized by numerous landslides, particularly shallow debris flow. With the preponderance of monsoon, the changing soil morphology and its physicochemical properties, the Western Ghats tend to have high drainage density and numerous cataclysmic landslides at a seasonal scale. In this terrain, the landslide studies are difficult due to the absence of fundamental mapping unit. Thus, this study aims to identify the basic mapping unit for landslide susceptibility mapping.

Methods: Identifying a typical area in the Western Ghats is an arduous task, but with the aid of recent literatures, we were successful in identifying an area, which is administratively located in the Idukki district of Kerala. The area encompasses Pettimudi landslide (77.01°E longitude and 10.17°N latitude), which occurred on 7 August 2020, killing 70 people. This landslide was induced by intense rainfall (5-day antecedent of 766 mm and a daily rainfall of 167). The study area is demarcated in such a fashion that it encompasses unique geomorphology, geology, slope or drainage basin. With a trial and error study on different terrain factors like geology, geomorphology, slope and drainage, we could identify drainage basin as an apt fundamental unit since it encompasses the entire landslides. In other cases it spills over to other units. Thus, a drainage basin of 26.43 sq. km is demarcated, which is a third order basin. The landslides occurred in this area during 2018, 2019 and 2020 monsoon were identified and mapped using high-resolution Google Earth images and through field investigation, which totals 42. The area is further subdivided into lower-order basins.

Results: Out of 42 landslides, 15 belong to first-order basin and 39 (cumulative) belong to second-order. The area of micro-watershed is 10.20, 17.36 and 26.43 sq. km for first-order, second-order and third-order basin, respectively. When computing the frequency of landslides in each basin, second-order basin has a frequency of 2.25 which is greater than other basins. The frequency of landslides in second-order basin is 52.80% more than the frequency in first-order basin and 41.41% more than that of third-order basin. The frequency of landslides in second-order stream basin is higher than first-order and third-order basins.

Conclusions: Since the frequency of landslides in second-order basin is more than that of other basins, we can reach to the conclusion that the second-order basin as the fundamental or basic mapping unit for the characterization of shallow-seated debris flow in this study area. The identified mapping unit can be further used to develop a landslide susceptibility map for the benefit of stakeholders involved in land use management and risk assessment.

AN APPROACH OF APPROXIMATION THE LANDSLIDE SCARP WHOSE TOE IS BURIED

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Purpose: This study aims at proposing an approach to approximating the landslide scarp in which the location of the toe of the rupture surface is buried. The coverage of the toe by the landslide mass may cause an annoying hurdle in identifying the size of the landslide scarp. It becomes challenging to estimate the released volume of the landslide mass as well. From the viewpoint of hazard assessment, it hinders the analysis of stability in back-calculation and the consequential flow paths, where a well-determined landslide scarp is generally beneficial.

Methods: We employ an idealized curved surface (ICS) proposed by Tai et al. (2020) to mimic the plausible landslide failure surface and to predict the flow paths in various scenarios. In Wang et al. (2022), it is found that the combination of the genetic algorithm (GA) and the ellipse-referenced-ICS (ER-ICS, Ko et al., 2021a) can help to identify the best-fitted ICS with respect to the set conditions in a high-efficient way. With the limited conditions (undetermined failure area, buried landslide scarp toe, pre-event and post-event DEM, etc.), we apply the GA-ER-ICS method (Wang et al., 2022) to the landslide scarp/area in a high degree of uncertainty and to suggesting various plausible scenarios for hazard assessment or detailed analysis.

Results: The feasibility of the present GA-ER-ICS is examined and validated by the plication to a historical landslide event, the Xiu-Luan Landslide that took place in north Taiwan on 13th Sep. 2021, where the analysis is based on the terrain data of a pre-event (LiDAR-derived DEM) and post-event (UAV-derived DSM) measurements and the toe of the landslide scarp is buried by the debris. In addition, together with the GPU-accelerated simulation tool and illustration system (Moses_2PDF, Ko et al., 2021b), one may examine the various scenarios in a 3D user-interactive way.

Conclusions: In spite of the high uncertainty in the exact boundary of landslide scarp and failure depths, the GA-EF-ICS method may reasonably provide plausible failure surfaces in various scenarios.

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A DATAHUB FOR COMPARATIVE RELIABILITY ASSESSMENT OF MODEL-BASED LANDSLIDE PREDICTION

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Purpose: Quantitative risk assessment of geomorphic hazards, in particular flow-like hazards of rapid and catastrophic nature, benefits extensively from advancements in computational process models, novel hardware development and an increased use of data science and artificial intelligence. Regional-scale affected area analyses at relevant spatial resolution, local-scale impact investigations based on complex high-fidelity models, and machine learning enhanced simulations facilitating high-throughput tasks or near real-time assessments are examples how modern computational modelling can be integrated into existing or to-be-developed risk assessment frameworks. While all these trends, in principal, increase our capability for robust and reliable risk assessment, we are currently facing a fragmented landscape of individual modelling technologies and uncoordinated model development efforts. Their comparison and integration are often challenging and require a substantial manual effort. There is an urgent need for standardised and holistic model-based landslide risk prediction workflows ensuring reproducibility of results, as well as systematic approaches for comparative reliability and robustness analyses. These workflows should be informed from and feed into an integrating data hub.

Methods: A plethora of workflow design criteria determine the outcome of a specific model-based landslide risk assessment, including fidelity level of the underlying process model, numerical solution approach, representation of topography, calibration method and prior distributions of model parameters. This study provides a structured and detailed analysis of this design space and facilitates comparative studies. Run-out simulations on synthetically-generated topographies and on real-world scenarios were conducted using an open-source GIS-based numerical solver. Landslide model parameters, i.e. parameter posterior distributions were estimated with different types of calibration techniques and data sources. Predictions were conducted based on forward propagating parameter and data uncertainty to estimate the reliability of risk assessment. Results from a large number of test runs are then integrated into a knowledge datahub to analyse reliability and robustness of the predictions.

Results: Early stages of the development of Datahub for Reliable Predictions in Geohazards (DRP-G) are presented herein. A prototype dashboard, serving as a user interface for DRP-G, demonstrates the reliability of landslide run-out predictions on synthetic and real-world topographies for different choices of the workflow design criteria. Examples of further functionalities, such as emulation in real-time, data integration over API, automatic metadata generation, are shown.

Conclusions: This study proposes an orchestrated effort for landslide risk assessment by combining complex forward numerical models, uncertainty quantification, parameter estimation, and surrogate modelling techniques. DRP-G serves as a platform for researchers, practitioners, and stakeholders (i) to collaborate on existing or new modelling frameworks, (ii) to create benchmark studies, (iii) to navigate uncertainties of a model-based risk assessment, and (iv) to investigate the reliability of assessments.

AN AUTOMATIC SLOPE UNITS DELINEATION SOFTWARE INTEGRATING A NEW METHOD BASED ON CONTOUR

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Purpose: China is one of the countries suffering the most serious landslide hazards in the world. Landslide susceptibility assessment is helpful for managers to formulate landslide prevention policies and reduce the loss of lives and property. As the basic unit of landslide occurrence, slope units have been widely used in landslide susceptibility assessment at large scale. Quick and automatic delineation method of slope unit is in great demand in recent years.

Methods: Contour method is proposed in this research based on the contour data, which delineates the slope units by establishing the contour tree, extracting and connecting the terrain feature points. Also, aiming at the automatic delineation of slope units, this paper develops an automatic delineation software named Slope Units v2.0 in Visual Studio 2019 based on ArcGIS Engine platform. Three methods including catchment watershed method, curvature watershed method, basin hill shade method and contour method are integrated in the Slope Units v2.0.

Results: Compared with the curvature watershed method and the basin hill shade method, the elapsed time of the contour method are reduced by 31s and 7 seconds under the same hardware (AMD R5-4600H and 16GB RAM). In the same study area, there is almost no fracture surface and missing surface, thus rarely need for user to correct results manually. And the contour method does not require any controlling threshold input. Comparing the results by calculating shape index and the proportion of shape index, the contour method is 89%, which is 6% higher than basin hill shade method and 10% higher than the curvature watershed method.

Conclusions: The contour method shows good performance and results in slope units delineation, and easy to use.

SESSION 3.1

RECENT ADVANCEMENT IN LABORATORY AND IN-SITU TESTING METHODS FOR LANDSLIDE AND SLOPE ANALYSES (part I)

THE CLAYS INVOLVED IN THE 1963 VAJONT SLIDE: MINERALOGY, GEOTECHNICAL CHARACTERIZATION AND GEOMECHANICAL IMPLICATIONS

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Purpose: The Vajont landslide that occurred on 9 October 1963 caused about 2,000 deaths when 270–300 Mm3 of rocks slid from the northern slope of Mt. Toc into the newly created reservoir, displacing some huge water waves that flooded the nearby villages. Basal sliding occurred within a lithostratigraphic sequence of cherty–marly limestones and clay interbeds belonging to the Fonzaso Formation of Upper Jurassic age. Although the 1963 Vajont landslide has been analysed from different scientific viewpoints, previous studies never examined the particular geological origin and provenance of the clays involved in the slope rupture.

Methods: We investigated the mineralogical (X-Ray Powder Diffraction), geochemical (X-Ray Fluorescence) and geotechnical properties of the Vajont clays according to the results of laboratory analyses performed on clay samples collected from the landslide failure surface and the surrounding area.

Results: The clayey materials contained variable amounts of clay minerals (36–96%), calcite (4–64%) and quartz (0–6%). The dominant clay minerals were illite/smectite (I/S) mixed layers with a high illite content (85–50%), which was consistent with the high percentage of K2O of the bulk (1.17–5.77%). Clay interbeds with a prevalence of clay minerals (CM > 79%) were characterised by low values of the residual friction angle (ϕres = 6.7–14.9°), whereas clayey materials with a large content of granular minerals had greater values of ϕres (19.5–26.7°). The Vajont clays included in the Fonzaso Fm. can be referred to as K-bentonites and can be interpreted as distinct deposits of volcanoclastic materials (tephra), representing the sedimentary inputs of volcanic ashes that interrupted the “normal” calcareous sedimentation during the late Oxfordian–upper Tithonian (158–145 Ma). The clay interbeds are the result of a temporal sequence of complex geological phenomena, including:

1) initial eruption and injection into the atmosphere of volcanic ash, probably from the Vardar Ocean back-arc or from the Crimea (Ukraine) subduction zone;
2) transport by wind and subsequent sedimentation in the Jurassic Vajont Basin; and
3) weathering and/or alteration of the original volcanoclastic material caused by diagenesis and burial-related phenomena.

Conclusions: Clay-rich interbeds within sedimentary sequences, especially those including smectite and/or mixed layers clays with low shear strength, represent a typical example in which a relatively minor geological feature has a major impact on the behaviour of the rock mass and the related slope stability condition. The Vajont clays played a different mechanical role in the occurrence of the prehistoric rockslide and the 1963 en-block remobilisation. When referring to the ancient slope failures, distinct clay-rich layers that were concentrated within some specific lithostratigraphic intervals of the limestone sequence caused a localised decrease in the available shear strength, allowing for relative shear displacements along the dip-slope bedding planes. This caused the formation of a stepped basal failure surface. During the 1963 remobilisation, the clay layers contributed to the average shear strength decrease of the debris material forming the basal shear zone of the slide, but the main triggering factor was the increase in pore pressures caused by the reservoir-induced groundwater inflow.

MITIGATION OF THE CATASTROPHIC QUICK CLAY LANDSLIDE AT ASK, GJERDRUM IN NORWAY, 30TH DECEMBER 2020

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Purpose: The catastrophic quick clay landslide at Ask in the municipality of Gjerdrum in Eastern Norway occurred on the night to 20th December 2020 and killed 10 persons and an unborned child. The volume was approximately 1.3 million m3, and the landslide debris had a maximum runout of 2 km. Mitigation of quick clay landslides is generally challenging, and landslide mitigation in quick clay is never without risk. Issues related to the techniques chosen for the mitigation work and the risk involved in the process will be presented.

Methods: To secure an area where a quick clay landslide has already occurred, the best possible information about the ground conditions in the landslide area is required, and geotechnical investigations should be performed. Ground investigations in a landslide area always involves some risk, and safety for personnel executing investigations must be maintained at a minimum level. Frequent collapses of the landslide scarp posed a substantial risk before proper stabilizing measures could be performed. Once ground conditions were mapped sufficiently, technical solutions for mitigation could be evaluated further. Careful unloading of tall and steep landslide scarps, combined with soil improvement of the completely liquified landslide debris, was chosen as the main solution for securing the area. The landslide debris consisted of up to 10 m of completely remolded quick clay, and construction work in the runout area proved, as expected, to be challenging. Bearing capacity of quick clay is generally very poor, since the remolded strength of the quick clay may remain low (below 0.5 kPa) for years after the slide if measures are not taken, because consolidation of the remolded clay is very slow. The general stability of the area after the landslide was hence also critical, with tall and steep landslide scarps, and a partly unknown distribution of disturbed and indisturbed quick clay in the ground. During construction work, the landslide pit was extensively monitored by piezometers and inclinometers. The development of the soil strength was investigated through repeated rounds of geotechnical investigations to check the effect of the ground improvement.

Results: Currently, the mitigation works are close to being finalized. The experiences gained from the mitigation work is useful for future approaches. Interesting data has been collected for reconsolidation and strength increase in remolded quick clay debris. Drones and ground-based radar, as well as rainfall thresholds, were used for monitoring and warning of potential failures along the scarp, as a tool to reduce risk related to the construction work, an d proved to be useful in keeping the risk level at an acceptable level.

Conclusions: Mitigation of quick clay landslides is costly and cumbersome and requires detailed geotechnical design and a careful construction process. The low remolded strength of quick clay must be considered. Proper risk evaluations are necessary, not only at the start of the work, but at several stages throughout the mitigation work.

RESEARCH ON FORMATION MECHANISM AND NEW PREVENTION TECHNOLOGY OF LANDSLIDE INDUCED BY HYDRO-FLUCTUATION BELT ROCK MASS DETERIORATION IN THE THREE GORGES RESERVOIR AREA

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Purpose: In the process of reservoir operation, periodic storage and drainage lead to the long-term and repeated fluctuation of water level. The rock mass in the hydo-fluctuation belt (HFB) is affected by the change of geological environmental conditions caused by the variation of water level, and its physical and mechanical properties change, resulting in the deterioration of rock mass. Since the Three Gorges Reservoir was impounded to the water level of 175 m in 2008, geological hazards caused by the deterioration of rock mass along the reservoir bank have been increasing continuously. This study focuses on the new problems and challenges of the geological safety of the Three Gorges Project threatened by the newly formed landslides due to the deterioration of the HFB rock mass.

Methods: Focusing on the key technical problems in the prevention and control of the HFB rock mass in the reservoir bank slope, the research on formation mechanism and new prevention technology of landslide induced by HFB rock mass deterioration have been systematically carried out through the combination of field investigation, numerical simulation, physical model test and multi-source field experiments.

Results: 1) There are two primary types of rock mass deterioration in the HFB: The deteriorations of carbonate rocks are mainly dissolution-suffosion, crack manifestation-extension, and mechanical erosion. While the deteriorations of clastic rocks are mainly loosening-spalling, erosion-abrasion, collapsing-block falling near structural planes, and weak strip interlayer denudation. 2) The mechanical models of rock mass deterioration mainly include equivalent continuous model and structural plane model. 3) Laboratory tests on the deterioration of rock microstructure show that both wetting–drying cycles and cooling–heating cycles lead to significant deterioration of rock mass. The mechanism of coupling effect to accelerate the deterioration of rock mass is proposed. With the increase of the number of wetting–drying and cooling–heating cycles, the mineral composition of rock mass will change, the surface mineral particles will flake off, the micro-cracks will constantly sprout and expand, and the porosity and permeability will continuously increase, leading to the gradual decrease of mechanical strength. 4) The maximum anchorage strength of large-tonnage basalt fiber-reinforced polymer anchor cable is 2023.79kN, indicating it can play a stable anchoring role in water-wading strata. As a kind of green and environmentally friendly lightweight anchor cable, it provides a new idea for the prevention of rock mass deterioration in the reservoir HFB.

Conclusions: The typical types, instability modes and mechanical models of rock mass deterioration in the bank slopes have been proposed. The early identification method of potential geohazards induced by the rock mass deterioration of HFB is established. The multi-field coupling mechanism for the ageing deterioration of the HFB rock mass is revealed. A new method for long-term stability evaluation of reservoir bank under the effect of rock mass deterioration is developed. And a new green prevention technology of 2000kN large-tonnage basalt fiber-reinforced anchor cable is invented. The relevant research provides technical support for the prevention and control of geological disaster risk during the operation of the Three Gorges Project.

SITE RESPONSE OF ANCIENT LANDSLIDES TO INITIAL IMPOUNDMENT OF BAIHETAN RESERVOIR (CHINA) BASED ON AMBIENT NOISE INVESTIGATION

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Purpose: When large reservoirs are impounded, the reactivation of ancient landslides significantly contributes to erosion. In this study, we investigated the site response of ancient landslides during the initial impoundment of the Baihetan Reservoir.

Methods: Ambient noise recordings collected at various reservoir water levels were analysed using the microtremor horizontal-to-vertical spectral ratio technique and single-station RayDec method. Furthermore, to explain the site response changes, we simulated the pore water pressure and stability of the S2# landslide using Geo-Studio software.

Results: Our results indicate that, with an increase in the early reservoir water level, the resonance frequencies and spectral ratio amplitude of landslides changed. However, the direction of site resonance did not change. We observed that the subsurface shear wave velocity of the slope decreased with an increase in reservoir water.

Conclusions: Our study provides a new method for analysing the site response of ancient landslides and a new perspective for studying landslide stability in reservoir areas.

INVESTIGATION ON THE PHYSICAL PROPERTIES OF THE LAYERED PYROCLASTIC COVERS INVOLVED IN SHALLOW LANDSLIDES IN CAMPANIA (ITALY)

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Purpose: Large mountainous areas of Campania (Italy) are characterized by hillslopes covered with layered deposits of loose pyroclastic materials, usually in unsaturated conditions, laying upon bedrocks with different characteristics. The pyroclastic covers, the stability of which is guaranteed by the contribution of soil suction to shear strength, are frequently affected by rainfall-induced shallow landslides, which cause heavy damage to property and infrastructures, and casualties. The presence of adjoining layers with contrasting texture, deposited during different eruptive phases of the two major volcanic complexes of the region (Somma-Vesuvius and Phlegrean fields), deeply affects rainwater infiltration (Damiano et al., 2017; Capparelli et al., 2020), and may also influence the triggering of landslides (Mancarella et al., 2012). A typical layered pyroclastic cover of the Apennines of Campania is represented in figure 1. Under an organic-rich topsoil, with dense roots, alternating layers of fine ashes (sandy loams) and coarse pumices (sands with gravel) overlay a deeply altered ashy layer, located at the contact with the underlying limestone bedrock. In this study, the results of experimental investigations on the major physical properties of the soils of the layered cover of the Partenio Massif, an area of the Apennines of Campania where recurrent rainfall-induced shallow landslides occur, carried out either in laboratory or in the field, are presented. Aim of the study is to provide data suitable to improve the predictive skill of physically based models used for landslide hazard assessment.

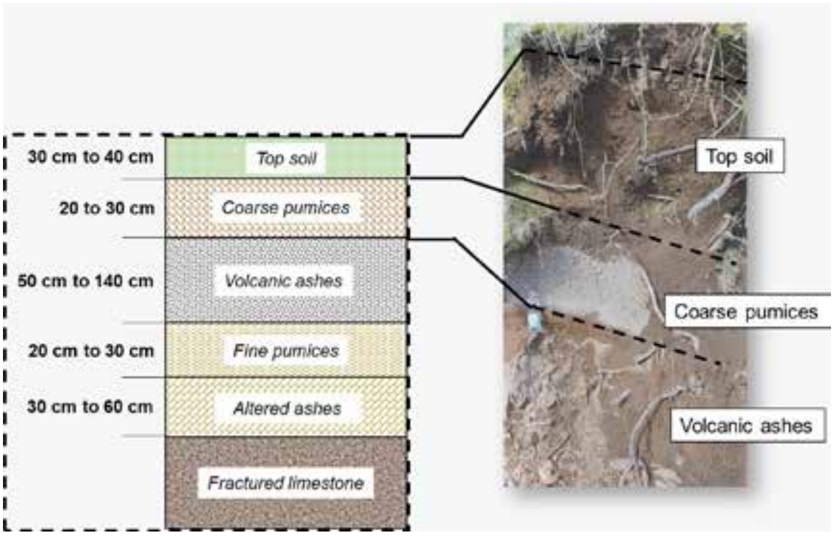

Fig. 1: Typical layered pyroclastic cover of the Apennines of Campania.

Methods: The reported laboratory experiments have been carried out on undisturbed and remoulded soil specimens, collected at two slopes where landslides recently occurred (i.e., Cervinara and San Martino Valle Caudina). Grain size distributions, water retention curves and hydraulic conductivity functions have been determined on samples taken from different layers of the pyroclastic cover. Water retention curves and hydraulic conductivity have been also estimated by back-analysis of infiltration tests carried out in small scale physical models of slopes, as well as from the interpretation of field monitoring data.

Results: The obtained results confirm that soils belonging to the same layer, collected at different places in the investigated area, show similar particle size distributions, water retention curves, and hydraulic conductivity functions. Conversely, the textural differences of the soils form different layers deeply affect their hydraulic and mechanical properties. Specifically, the altered ashes at the contact with the underlying limestone bedrock, which show a much finer granulometry, compared to the ashes of the other layers, exhibit higher plasticity, smaller conductivity, and much higher capability of retaining water at large values of suction.

Conclusions: The collected experimental results confirm the strongly different hydraulic properties of the soils belonging to different layers (ashes, pumices and altered ashes) of the pyroclastic covers of the Apennines of Campania. These differences may deeply affect unsaturated flow processes, and they should be considered in the parametrization of physically based models aiming at the detailed simulation of rainwater infiltration.

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ROCK SLOPE STABILITY ANALYSIS THROUGH ON-SITE METHODS: DATA FROM CSIRO HI CELLS TESTS FOR CALIBRATING 3D NUMERICAL MODELS

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Purpose: The main aim of the present study is to evaluate the stability of some marble quarries in the Apuan Alps (Italy) through three-dimensional geometric reconstruction, numerical modelling and calibration of the stress states acting on-site. This research is developed through both in-situ and laboratory investigation techniques, whose results enabled to obtain an in-depth knowledge of the acting stress states (3D stress tensor) and the material elastic properties. The data obtained from these methods allowed us to carry out the stability analysis and therefore to ensure workplaces safety for the personnel involved in mining activities.

Methods: The proposed method of investigation is based on: i) the acquisition of the geometric information of the quarry slopes using geo-referenced surveys acquired by terrestrial laser scanner and/or UAV (Unmanned Aerial Vehicle); ii) the acquisition of data about the characteristics of the rock mass through engineering-geological surveys and laboratory tests; iii) the on-site measurement of the acting stress states through CSIRO HI cells tests; iv) the creation of the rock masses 3D numerical models, including their calibration, and the simulation of the various future excavation phases. The data achieved from the various activities flowed into a series of models simulating the geological and stress conditions of the various fronts, whose stability was analyzed by applying both methodologies of distinct elements (DEM), using 3DEC (Itasca®), and finite elements (FEM), using RS3 (RocScience®).

Results: The strain and stress measurements conducted on site were used to calibrate the models through a reiterated procedure written ad hoc using the MATLAB® language. For each model, the analysis of the stress states, the displacement vectors, the deviatory stress and, consequently, the stability of the slope was carried out in temporal sequence, starting from the initial conditions up to the final state as from the excavation plan.

Conclusions: The integrated approach of on-site measurements and geological analyses through 3D numerical modelling, allowed us to define the stress state acting in some quarries of the Apuan Alps' marble complex. Thanks to the numerical modelling, appropriately calibrated and validated with the on-site stress state measurements, a faithful stability analysis was carried out. This research approach came out suitable for detecting and monitoring, even during the excavation activities, the stress-strain behaviour of the rocky walls and for guaranteeing a safe workplace for the personnel involved.

SHEAR SURFACE UNDULATIONS MODULATE GOUGE STRENGTH AND CONTRIBUTE TO DIVERGENT LANDSLIDE ACCELERATION

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Purpose: Landslides display a broad spectrum of speeds for incompletely known reasons. Sliding occurs along slickensided undulatory shear surfaces within boundary shear gouge. Laboratory tests reveal that gouge shear resistance generally decreases with finite cumulative displacement during relatively rapid failure (>10-5 cm s-1) and may increase or decrease with increasing shear rate. Understanding mechanisms responsible for these diverse behaviors remains elusive but critical because such strength variability can result in accelerating or decelerating landslide failure. We performed advanced laboratory shear-strength testing that revealed such variations in shear resistance of various silt-clay mixtures comprising a landslide near Oso, Washington, USA. We hypothesized that millimeter-scale undulations along shear surfaces impart shear resistance by presenting geometrical interference to shear displacement, similar to what occurs at the smaller particle scale and the much larger scales along irregular landslide shear boundaries and bends in tectonic faults. Geometrical interference also modifies stresses at these other scales, thus we further hypothesized that the stress modification at the shear-surface undulation scale modifies particle-scale shear resistance.

Methods: We tested our hypotheses in the laboratory using an advanced, large ring-shear testing apparatus and using finite element modeling.

Results and Conclusions: Results revealed that undulation-induced dilative weakening can explain the strength degradation with finite displacement that occurs during renewed failure following periods of inactivity. Rapid shearing across undulations persistently elevates pore water pressure and reduces effective normal stress through local dilation. Overall effects differ by material with granular-rich, high-friction material losing resistance with increasing shear rate, and clay-rich, low-friction material losing little or gaining resistance as shear rates increase. Gouge with little clay may not develop undulatory shear surfaces, resulting in invariant shear resistance. Ample testing by others using various shear-testing apparatuses and materials supports these conclusions. The propensity for accelerating or decelerating shear gouge failure may be estimated from simple index tests of clay-size content or Atterberg limits. Hence, our findings reveal previously unknown mechanisms that may explain divergent landslide behavior and improve the ability to forecast whether future landslides are likely to move slowly and episodically or rapidly and catastrophically.

DEVELOPMENT OF A NEW RING SHEAR DEVICE FOR INVESTIGATING SHEARING RESPONSE OF FLOW-LIKE LANDSLIDES WITH PORE PRESSURE FEEDBACK

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Purpose: Flow-like landslides are composed of fluid and granular materials. Relationship between shearing and pore pressure generation/dissipation is fundamental in predicting behaviour of flow-like landslides. The kinematics of flow-like landslides during initiation, propagation, interaction with various boundary conditions and impact with mitigating structures are predominantly governed by timescales of generation and dissipation of pore fluid pressure. Hence, it is of fundamental importance to understand dynamics of granular shear behaviour coupled with pore pressure feedback. The shearing of flow-like landslides differs from the shearing during landslide initiation, because shearing is not limited to shear band in flow-like landslides. Several shearing devices have been designed and tested to model shear behaviour of landslides and granular flows. However, existing devices are (i) designed for studying shearing behaviour in a predefined shear band and (ii) limited to using maximum particle size of around 4.5 mm.

Methods and Layout of the device: A new ring shear device has been designed, manufactured, and installed in The Hong Kong University of Science and Technology to investigate granular shear behaviour of flow-like landslides. The ring shear device has an annular space of 0.15 m width and 0.23 m depth for test material with 1.2 m diameter outer wall. The inner wall is made up of steel and outer wall is made up of transparent acrylic. The test material is sheared by rotating the top plate. The device includes pore pressure control and measurement system using a pump and three pore pressure transducers fixed at the base of the annular space. Additional pore pressure transducers are installed vertically along the sample height in the middle of the annular space to measure dynamic pore fluid pressure gradient. In addition to pore pressure measurement, volume change during shearing is measured using change in the level of the rotating top plate from three laser sensor readings. The device is designed to perform both normal stress controlled tests and constant volume tests using closed loop proportional integral derivative (PID)-control of hydraulic actuator movement. In this study, granular material with diameter of up to 25 mm is adopted.

Results: This study demonstrates the capability of the ring shear device in capturing change in dynamic pore pressure, normal stress, shear stress and volume change independently during steady state shearing. The servo-actuator motion control system shows excellent performance in controlling volume and normal stress levels during tests.

Conclusions: A steady state shearing of flow-like landslide with a depth of up to 2 m can be modelled using the new ring shear device, which shows great potential in future uses for studying shearing response of flow-like landslide considering evolution of dynamic pore pressure.

SESSION 2.11

ENHANCEMENTS IN LANDSLIDE DATA ANALYSIS FOR IMPROVED UNDERSTANDING, FORECASTING AND EARLY WARNING SYSTEMS (part I)

A NEW CONCEPT FOR PROSPECTIVE FAILURE TIME FORECASTING

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Increasing rock slope failure activity and growing safety requirements boost the demand for reliable failure time forecasts. Nowadays, modern monitoring systems can deliver displacement observations in (near) real-time at high spatial and temporal resolution. But so far, existent prediction models need amendments to be able to handle such data and to provide unambiguous forecasts. In a prospective approach (pre-failure), data filtering, starting point definition and forecast uncertainty often remain arbitrary.

Here, we present a new concept for prospective failure time forecasting based on the linear inverse velocity method. It is designed to operate fully prospectively in real-time and is implemented into an open-source R-code. By applying multiple filtering windows and inverse velocity percentiles, we can minimize subjective decisions, detect the onset of acceleration automatically, and statistically estimate the uncertainty of each forecast.

We test the concept with 14 historic rock and ice failures of 10^2-108 m^3 including 46 datasets from different sensors (Global Navigation Satellite System, total stations, displacement meters, inclinometers, radar). The algorithm automatically detects the onset of acceleration sufficiently early 0.1-200 days before failure. The forecasts match the actual failure time of all events with errors of less than a day for sub-daily data and -1±4 d for daily data indicating an overall better performance with higher sampling frequencies in combination with adequate filtering. We also test the sensitivity of the forecasting to the linearity of the inverse velocity trend extrapolation and the timing of the starting point.

This prospective approach overcomes previous problems by introducing a robust and uniform forecasting concept across various types of catastrophic rock slope failures and sensors. Its application might not be limited to rock slopes, but the underlying physical principle might also be valid at earth slopes, man-made slopes, artificial structures, and glaciers, thus supporting decision-makers in a multitude of critical situations.

ANOMALY DETECTION USING ELASTIC NET FOR SLOPE STRAIN MEASURED BY CENTRIFUGAL MODEL TEST

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Purpose: As a soft measure to prevent sediment disasters, various measurement devices and monitoring systems have been developed through improvement of ICT technology, and systems to detect signs of collapse and encourage evacuation have been developed based on real time monitoring data for slope movement. A major challenge in those systems is what kind of measurement indicates a sign of danger. The objective of this research is to determine if a slope has reached a dangerous state, rather than to predict a specific time of slope failure.

Methods: In this study, a method for detecting anomalies on a slope was verified by using machine learning, in which data is predicted from time series of slope surface's strain data measured in a slope failure experiment using a centrifuge, and by using the residuals between the predicted and measured data. The Elastic Net was used among machine learning models. In the experiment, a centrifugal acceleration of 50 G was applied to the model slope with 12.5 m height. The used soil, decomposed granite soil from Kasama, Ibaraki Prefecture, Japan, was passed through a 2-mm sieve the optimum water content was set at 17.3%, and the soil was compacted into four layers with a dry density of 1.50 g/cm3. Eight surface strain sensors were installed on the slope, which are made of 0.1mm thick steel plates (model scale) with strain gauges attached to both sides of the plates. After centrifugal acceleration reached 50 G, 13-step slope excavation was performed (see Figure1). As a method for evaluating slope monitoring data, a machine learning method was employed using slope monitoring data in a normal state during slope stability, and when a pattern of data different from the normal state was detected, the slope was considered to be unstable and an alert is issued.

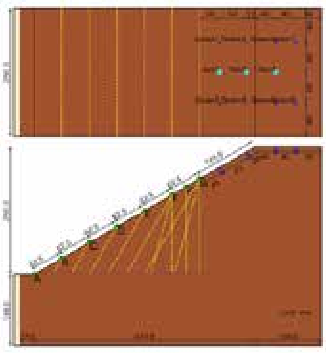

Fig. 1: Experimental model.

Fig. 2: 3rd collapse.

Results: In this experiment, slope failure occurred after the 6th (6865s), 8th (9145s), and 10th (11888s) excavations (see Figure2). The surface strain results strain2, were used to study anomaly detection (see Figure3). It was found that anomalies can be detected before the first collapse. The model learned by the measurement results of strain2 was applied to the other channels (see Figure4). As a result, it was confirmed from the time series change in the number of anomalies detected by the eight installed surface strain sensors that anomalies on the slope were detected before the collapse.

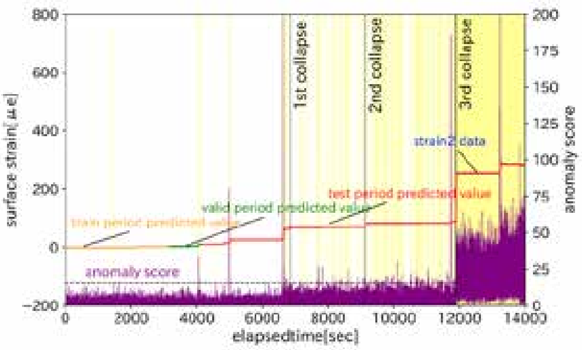

Fig. 3: Strain 2 anomaly detection result.

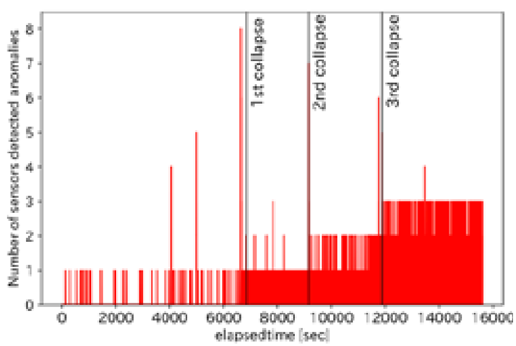

Fig. 4: Number of sensors detected anomalies.

Conclusions: This study evaluated a method for detecting anomalies from residuals between measured and predicted values using surface strain time-series data. The results of this study show that it is possible to detect anomalies before slope failure by machine learning. However, there still have issues in anomaly detection in terms of determining the degree of anomaly and setting threshold values. In the future, it will be necessary to examine and compare the machine learning models suitable for natural and working environments.

AUTOENCODER-BASED ANOMALY DETECTION FOR MONITORING DATA IN A FULL-SCALE MODEL SLOPE TEST EXCAVATION

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Purpose: To prevent industrial accidents caused by landslides during excavation work, slope movement is monitored by measuring equipment installed on the slope. There are two ways to utilize this data: one is to quantitatively evaluate the deformation and review the construction plan, and the other is to judge whether to evacuate the slope when it is dangerous. The evacuation judgment is very important, but no algorithm has been established to determine when data changes to define danger. In this study, a full-scale slope was excavated and collapsed, and monitoring data obtained during the excavation were used to examine whether anomaly detection is feasible.

Methods: A full-scale slope experiment was conducted using Kanto loam with a height of 3.5 m and a slope gradient of 30° as shown Figure 1. The slope was excavated by a drag shovel to cause a collapse. Thirty sensors (inclinometers, extensometers, surface strainmeters, and displacement transducers) were installed on the slope to acquire data during the collapse. This monitoring data was analyzed using AutoEncoder, a type of deep learning. The velocity of sequence data from each sensor was converted into sub-sequence data by means of a sliding window, and evaluated by the residuals between the input values and the reconstructed data using AutoEncoder. The sequence data were divided into three parts: training, validation, and test. The anomaly was defined by the mean and variance of the residuals during the validation period.

Results: The trends of the measured data, the reconstructed data and anomaly scores at one inclinometer sensor are shown in the figure 2. The anomaly score increases before the collapse, indicating that the slope collapse can be detected in advance. In this experiment, 42 features were obtained from 30 sensors, all of which were subjected to anomaly detection by AutoEncoder. The time-series of the number of sensors that detected anomalies is shown in the figure 3. Note that some of the sensors were removed due to the collapse after the fifth excavation, and the upper limit of the number of features obtained has changed. The hatch is set at an arbitrarily determined 30% of the maximum number of anomaly detections obtained, and it can be seen that it is generally dangerous when the number of anomalies exceeds this line.

Conclusions:

An anomaly detection method based on the deep learning AutoEncoder model was applied to an excavation experiment on a full-scale slope. The model used in this study was not tuned for hyperparameters. Even so, we were able to construct a model in which the anomaly score increased before the collapse, and showed an example of an algorithm with high generalization performance. However, it is necessary for the administrator to decide how many anomaly sensors should be evacuated when the number of anomalies detected reaches a certain number, and such decisions should be made in accordance with the situation.

Fig. 1: Full-scale slope model test. a) initial time, b) The third collapse

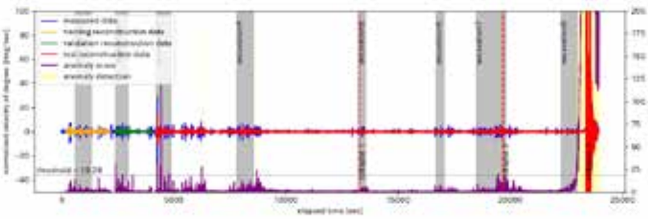

Fig. 2: Anomaly detection results from analysis of data from a inclinometer

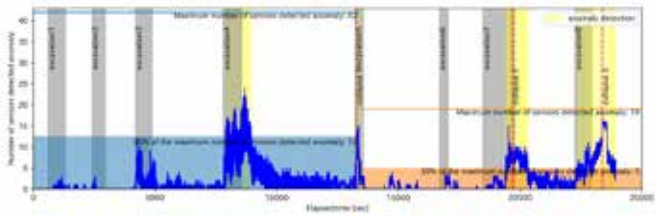

Fig. 3: The time-series of the number of sensors that detected anomalies

AI ENABLED IOT BASED LANDSLIDE EARLY WARNING SYSTEM INTEGRATING CROWD SOURCING AND COMMUNITY

AI ENABLED IOT BASED LANDSLIDE EARLY WARNING SYSTEM INTEGRATING CROWD SOURCING AND COMMUNITY RESLIENCE RESLIENCE

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Purpose: India has experienced extreme weather conditions during the recent years, 2018 - 2022, leading to large scale multi hazard events. These events have led to cascaded landslide events of multiple variations including rockfalls, debris slides, mudflows and other complex landslides several of them leading to loss of human life and large scale infrastructure damage. Climate change is contributing to an increase in extreme weather conditions aided with uncontrolled anthropogenic activities leading to an increase in the frequency of landslides, and its unpredictability.

Methods: This demands design, development and deployment of early warning systems for enhancing disaster resilience of the community. With a rapid advancement in the domains of IoT, AI, Big data, research disciplines have put in place measures to increase the reliability and accuracy of their findings. In this work we discuss the AI algorithms that were used for successful early warning at Sikkim Himalayas and Western Ghats, India. These algorithms include integrating site specific and regional thresholds with nowcasting and forecasting technology to arrive at multilevel early warning to the community. These AI algorithms have also served the purpose of establishing edge intelligence, extended lifetime of the system, fault tolerant data, nowcasting, forecasting framework which can handle no data availability situation, ahead of time warning, less false positive warning, etc. Development and continuous enhancements in Crowd source mobile applications i.e. AmritaKripa and Landslide Tracker based on uses and feedback is essential and showcased in our study areas.

Results: The results from these two case studies, one of Munnar, Kerala, and the other of Chandmari, Sikkim from India provide insights about the efficacy of the AI enabled IoT system to provide reliable early warning more efficiently. The system has so far given early warnings in 2009, 2013, 2018, 2019, 2021 and 2022 to the Munnar community through the Government. After these warings landslides have occurred in the area which indicates the validation of the warnings delivered by the system. Additionally, utilizing the strategically deployed sensors data and their interpretations we are able to work out mitigation strategies of some of these vulnerable areas.

Conclusions: This multiscale, multidimensional AI enabled IoT systems can be customized and scaled to be implemented at multiple levels in other parts of the world to monitor and early warn landslides and other multi hazards.

EXAMINATION OF INVERSE VELOCITY METHOD IN FORECASTING FAILURE TIME AGAINST METHODS OF SLO AND VELOCITY OVER ACCELERATION

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Purpose: One of the main tasks of landslide monitoring systems is forecasting failure time proactively. This assignment is often conducted by extrapolating the abscissa of the fitted line on the inverse velocity values vs. time following Fukuzon's method (1985) where the curvature indicator ( ) equals two. Although numerous studies have supported this approach, especially in the final stages of a slope life, posing such an assumption on a landslide with non-linear behaviour could lead to excessively inaccurate estimations. Also, exercising such an assumption relies heavily on accurately detecting the onset of acceleration and consequently fitting a function that is not bounded by a strict =2 presumption would be advantageous. However, the application of a non-linear inverse velocity method faces several mathematical issues (e.g., ill-posed conditioning and saddle points). By-passing the parameter is consequently a necessity by employing other variants of the inverse velocity method; including the SLO method (derived from "Slope", Mufindarwa et al., 2010) and Velocity over Acceleration (VoA) method (Hao et al., 2016). The objective of this paper is to evaluate the accuracy of regular inverse velocity (RINV) in comparison with SLO and VoA methods in light of instrumental and natural scatter.

Methods: To achieve this, 80 time-series displacement or velocity data of historical failures are collected from the literature and examined along with a comprehensive numerically generated database.

Results: The results show that employing SLO and VoA methods improves the accuracy of failure time forecasts on average by 96 and 47% compared to RINV. Further, it is observed that assuming a finite velocity at the moment of failure, contrary to RINV which assumes infinite velocity, also improves the accuracy of forecasts by 74%.

Conclusions: It is suggested that RINV's alternative to be considered for implementation in monitoring strategies such as early-warning systems.

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PREDICTION OF SLOPE FAILURES BASED ON MASSIVE AND MULTI-TEMPORAL INVERSE VELOCITY ANALYSIS OF SATELLITE INSAR AND GROUND-BASED RADAR DATA

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Purpose: The inverse velocity method represents the most used and successful approach to estimate the time of failure of accelerating slopes. The objective of this paper is to present a new method to identify approaching failure conditions through the implementation of the inverse velocity analysis carried out over spatially distributed monitoring datasets and over multiple temporal scales, such as those collected by ground-based radar and satellite InSAR.

Methods: The proposed method takes advantage of the spatially distributed nature of monitoring data collected by satellite InSAR and ground based radar and of their different acquisition frequency and temporal coverage. Those technologies provide spatially distributed monitoring data covering multiple temporal frames (from years to hours) with the highest sensitivity to movements (from mm/y to mm/day), thus allowing an early identification of trend changes. By using those technologies and by processing all their data at different temporal scales, routinely and extensively thanks to the processing power offered by cloud based servers, in order to benefit of their areal distributed nature, maps showing spatially consistent areas where data are matching the inverse velocity method can be generated. The goal of the method is to extend the usability of inverse of velocity analysis to detect progressive trends over massive datasets of data. In fact, the analysis is run routinely over all the measurement points provided by the entire monitoring datasets and not on a priori point selected by the user where progressive trends have been identified. Furthermore, the described approach is multi-temporal. The regression coefficient of the linear interpolation of the inverse velocity in fact changes with the time interval used to calculate it. To avoid the introduction of any bias in the results, the time interval is not fixed and predefined, but it is calculated for different temporal scales. The regression coefficient is calculated for all the possible time windows, from the last few acquisitions up to the entire time series.

Results: The method is routinely used in operational contexts to support the identification of approaching failure conditions on slopes of open pit mines, quarries, tailings dams and on natural slopes. A few case studies of the application of the method to different slope instabilities and using either satellite InSAR (Figure 1) and ground based radar data (Figure 2 and Figure 3) are presented in this paper, demonstrating how the method can be used to identify areas of concerns and support the activation of a response plan, as well as for back analysis to support forensic investigations.

Conclusions: The proposed method based on the extension of the implementation of the inverse velocity method from a few manually selected points to spatial distributed datasets with hundreds of thousands of measurement points and from pre-defined temporal intervals to all the possible temporal scales of the failure process, does allow practitioners dealing with landslide forecast, to move from a reactive to a proactive monitoring approach, providing for those areas where progressive displacements are detected, maps of the dates produced by the intersections with the time axis of the inverse velocity linear trend.

Fig. 1: On the left InSAR points of an undisclosed open pit classified based on their regression coefficient to the linear inverse velocity are shown, while on the right the expected failure time grouped by months of the InSAR points with the highest R2.

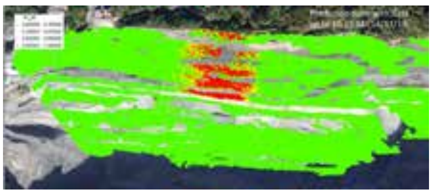

Fig. 2: Groudn based radar data of a quarry classified based on the regression coefficient to the linear inverse velocity 30 min before a collapse, indicating the area where the radar data are matching with the linear inverse velocity.

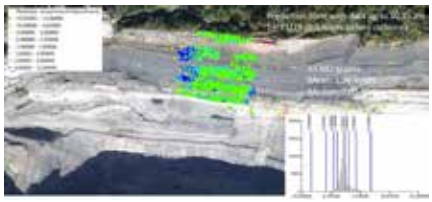

Fig. 3: Groudn based radar data of a quarry classified based on the difference between the predicted and the actual time of failure, 30 min before a collapse.

PROCEDURE OF DATA PROCESSING FOR THE IMPROVEMENT OF FAILURE TIME PREDICTION OF A LANDSLIDE BASED ON THE VELOCITY AND ACCELERATION OF THE DISPLACEMENT

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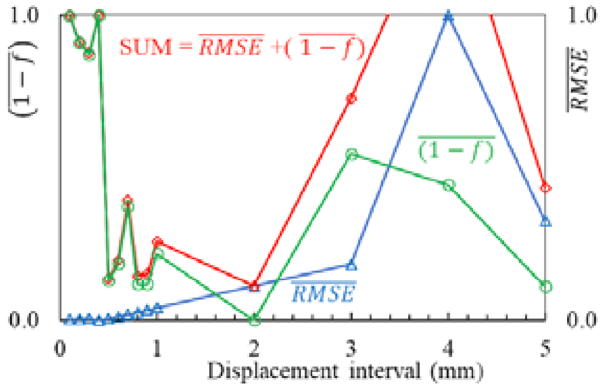
Purpose:

Time prediction methods based on monitoring the displacement are effective for issuing an early warning against rain-induced landslides. In this regard, past literature highlighted the importance of data filtering because the displacement noise amplifies the resultant velocity fluctuation, causing less accuracy in predicted failure time (tr). Therefore, the present study aims to introduce the data processing procedure to obtain better prediction by minimizing the influences of the velocity fluctuation on the predicted tr.



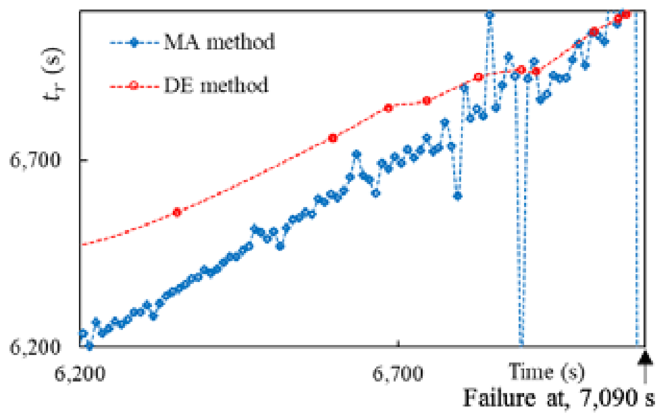


Fig. 1: Normalized RMSE, ($\overline{RMSE}$) and normalized (1-f), ($\overline{1\text{-}f}$) value variation with differente intervals for SD data extraction

Fig. 2: The comparison of time variation predicted tr by VAA

Methods: The measured surface displacement (SD) using small- and large-scale indoor model slope experiments under a rainfall simulator are utilized for the analysis. The measured SD is treated by the data extraction (DE) and moving average (MA) methods to improve the better smoothness of the time variation of inverse velocity (1/v). Finally, the data, treated by the DE and MA methods, are utilized to predict the tr based on Fukuzono's inverse velocity (INV) method and the method based on velocity and acceleration using linear regression analysis (VAA). The root mean square error (RMSE) and determining factor (f) are used as the parameters to select the optimum displacement interval (Δx) in the DE method. RMSE is used to assess the reproducibility of measured data. When the (1-f) gives the lowest value, the relationship between velocity and acceleration reaches the lowest scattering. Although the (1-f) always lies between 0.0 to 1.0, RMSE is changed depending on the displacement interval used for the DE. So, both values are normalized into the same range, 0.0 to 1.0, assigning the weight ratio 1:1 between RMSE and (1-f), as shown in Figure 1. The moving average of inverse velocity ($\overline{1 - v}$) values are used to smooth the time variation of 1/v in the MA method. In this regard, ($\overline{1 - v}$) values are calculated by considering different consecutive values and selecting the best consecutive value, which gives the best smoothing time variation of ($\overline{1 - v}$).

Results: The study reveals that raw data preprocessing is necessary to minimize the scattering of the predicted tr. The DE method combined with the VAA prediction gives the best result compared to others (Figure 2) with smaller fluctuation than MA method. The optimum Δx in the DE method provides at the lowest summation of ($\overline{RMSE}$) and ($\overline{1\text{-}f}$). The better smoothing of the time variation of the inverse velocity curve is obtained from the moving average of inverse velocities calculated by a larger number of consecutive inverse velocities than a small number of consecutive inverse velocities. However, the time prediction using data processed by the MA method shows poor prediction.

Conclusions: The failure prediction by the VAA method using DE preprocessing gives the best prediction because it minimizes the individual velocity variation. In the process of DE, not only reproducibility but also equal priority is given to reducing the scatter in the relationship between velocity and acceleration.

SESSION 6.6

ADVANCES IN UNDERSTANDING, QUANTIFYING AND MODELING THE CONTRIBUTION OF PLANTS TO SLOPE STABILITY

STATE-OF-THE-ART: PARAMETRIZATION OF HYDROLOGICAL AND MECHANICAL REINFORCEMENT OF ROOTS IN SLOPE STABILITY MODELS

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Purpose: The use of vegetation as a nature-based solution for shallow landslide risk reduction is receiving increased attention in the scientific community. Vegetation can contribute to slope stability through both hydrological and mechanical root reinforcement, improving resilience against shallow landslide triggering. In order to quantify the performance of roots as a slope stabilizing measure, slope stability models are valuable tools. Murgia et al. (2022) conducted a thorough review of existing physically-based software that consider the mechanical effect of roots in the calculation of factor of safety. Their study focused on highlighting the identified models' scale of application, dimension of calculation, and which geotechnical and hydrological models the software are built on. Bordoloi and Ng (2020) conducted an extensive review on both the influence of mechanical and hydrological traits of vegetation on slope stability, focusing on how these effects have been quantified through in-situ measurements, laboratory analysis and modelling. None of the mentioned studies did, however, go into depth in describing how the governing processes of root-soil interaction in shallow landslide triggering are parametrized in existing modelling software.

Methods: This study builds on the previous reviews by identifying existing software that considers both mechanical and hydrological effects of roots on slope stability. The different software are analyzed with emphasis on how the governing processes of shallow landslide triggering are parametrized in the identified software. Moreover, a review of the applications of the different software is conducted by performing literature search in peer-reviewed databases. This part of the review focuses on identifying the number and specifics of applications of each model. Finally, a selection of the identified models is tested by back-calculation of a shallow landslide event located in Aurland, Norway. Aurland is situated by fjords and mountains with small populated areas concentrated in the lower river valleys. The area is known to be prone to landslides in steep terrain.

Results: This study provides an in-depth comparison on how the hydrological and mechanical reinforcement of roots on soil is parameterized in existing slope stability models. The review of the number and specifics of applications of each identified model provides an insight on what is the common practice for modelling slope stability when accounting for the effect of vegetation. The validation of a selection of the models by application to the above-mention shallow landslide event in Aurdal will provide a direct and visual comparison between the models.

Conclusions: This review will serve as a base to develop a guideline that will ease the decision-making process when deciding which model to use for the slope scale; mitigation measures for a specific slope is to be designed, and for the catchment scale; when land-use plans for regions are to be developed.

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MECHANICAL IMPACTS OF FOREST VEGETATION ON SHALLOW LANDSLIDES CONSIDERING ITS SPATIAL DISTRIBUTION IN A MOUNTAIN WATERSHED

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Purpose: Recently, many studies have been carried out to quantify the mechanical impacts of vegetation (i.e., tree surcharge and root cohesion) as the input parameters of shallow landslide susceptibility modeling. However, at a regional scale, accurately estimating the characteristic values of vegetation parameters remains challenging. This study aimed to calculate the realistic values of vegetation parameters at a regional scale by considering the spatial distribution in the field, and to conduct quantitative analysis on the mechanical impacts of vegetation through back analysis on past landslide-damaged areas.

Methods: The study site is 26 ha of forested mountain watershed located in Jecheon-si, South Korea, where seven shallow landslides were caused by heavy rainfall on August 2, 2020. The revised TRIGRS 2, modified to consider the vegetation influences, was used in the study. As the input parameters, the vegetation parameters, namely, tree surcharge and root cohesion, were calculated through information on tree species, diameter at breast height (DBH), and density from 1:5,000 digital forest stock maps or the drone orthophotos. Finally, the TRIGRS 2 simulation was conducted with three scenarios depending on the method of considering vegetation parameters: 1) Not considering them (VO scenario), 2) Considering them generated from tree density based on the existing digital forest stock maps (V1 scenario), and 3) Considering them generated from tree density based on the drone orthophotos (V2 scenario). The results of the scenario analysis were compared by the average value of factor of safety (FS), the ratio of FS < 1 cells, hit rate, and area under the curve (AUC).

Results: A significant difference was found in the results of estimating tree density between two different methods. The average value of the entire watershed was 721 trees/ha for the V1 scenario, but 184 trees/ha for the V2 scenario. Accordingly, the average value of tree surcharge (V1: 221 Pa, V2: 52 Pa) and root cohesion (V1: 2,406 Pa, V2: 802 Pa) were also calculated to be higher in the V1 scenario than in V2, indicating that V1 was overestimated, unlike the actual situation in the field. As a result of the TRIGRS 2 simulation for each vegetation scenario, the average FS values of the watershed were 1.3573 for V0, 1.5859 for V1, and 1.4342 for V2, and the ratio of FS < 1 cells were calculated as 66% for V0, 7% for V1, and 52% for V2. As indicators of the accuracy of the simulation results, V0 was calculated as 1, V1 was 0.5714, and V2 was 1 in the hit rate, and V0 was calculated as 0.6824, V1 as 0.7704, and V2 as 0.7440 in the AUC.

Conclusions: The results confirmed that the mechanical impacts of vegetation played an important role in the occurrence of shallow landslides, and that precise calculation of vegetation parameters affected the accuracy of shallow landslide susceptibility modeling. They also implicated the possibility that both accuracy and reliability could be enhanced when realistic values of vegetation parameters were estimated based on the spatial distribution of trees in the field.

A PROBABILISTIC MODEL FOR SLOPE STABILITY ANALYSIS INCLUDING THE ROOT REINFORCEMENT EFFECTS

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Purpose: The presence of vegetation plays an important role in slope stability, especially in triggering of shallow landslides. It influences the mechanical and hydrological behaviour of soils, generating both stabilizing and destabilizing actions (Pollen-Bankhead et al., 2010; Masi et al., 2021). Taking into account the presence of vegetation in Slope Stability Models (SSMs), in addition to quantifying the factor of safety, allows to evaluate the effects of land-use changes and anthropogenic disturbance for better land management (Murgia, 2022).

Methods: In this study we implement a module for the calculation of root reinforcement in the slope stability physically-based probabilistic model called PG_TRIGRS (Probabilistic, Geostatistic-based, TranSient Rainfall Infiltration and Grid-based Slope stability, Salciarini et al., 2017). Such model allows the wide-area assessment of the probability of rainfall-induced failure, considering the spatial variability of the PDF (Probability Density Function) of the soil properties over the study area. In this work we apply the model to an area predisposed to landslides in the Umbria region (Italy) considering the spatial variability of soil properties and vegetation.

Results: To investigate the influence of the spatial layout of plant roots on slope stability, the probabilistic physically-based stability model is applied including different sets of soil mechanical and hydraulic parameters assigned as random variables, depending on different slope covers considered. The resulting probability of failure distributions is compared to (i) the results obtained for the bare soil (absence of roots), (ii) the results for different stages of plant growth and (iii) observed or derivable data from satellite measurements.

Conclusions: In this study we propose a probabilistic approach to assess the effect of vegetation on slope stability at large scale.

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PROBABILISTIC ANALYSIS OF ROOT-REINFORCED SLOPES WITH INTELLIGENT SURROGATE MODELS

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Soil-bioengineering methods are successful nature-based solutions for the stabilization of slopes susceptible to shallow landslides. Modelling the effect of root reinforcements on slope stability is a complex task due to the interplay of several processes, e.g., evapotranspiration and the interaction between soil and plant. Moreover, high uncertainty surrounds the estimation of soil properties and root reinforcement parameters, which is often disregarded in slope stability analyses. While full probabilistic approaches, such as Monte Carlo simulations, offer a conceptually straightforward method of implementation, they can be computationally demanding, especially when applied to complex deterministic models. One strategy to tackle this challenge is the use of surrogate models that can approximate the nonlinear relationship between input model parameters and slope performance indicators.

Purpose: In this study, we adopt a probabilistic approach to address the inherent uncertainty of root constitutive parameters and hydraulic soil properties of root-reinforced slopes. A coupled hydro-mechanical model considers the combined effect of mechanical root reinforcement and water root uptake in unsaturated soils. The infiltration of rainfall is modelled to assess landslide triggering over time.

Methods: Failure is defined as the exceedance of a displacement threshold at the slope toe, which is calculated by the coupled hydro-mechanical model using the finite element method. Root constitutive parameters and hydraulic properties are treated as random variables with assigned probability distributions. Sample values of these variables are first generated with the Latin Hypercube Sampling technique, which is more efficient than random sampling. These data serve as a training set for the surrogate models based on machine learning algorithms, which aim to predict resulting displacements with significantly lower computational effort. Four algorithms are tested as surrogate models: linear regression, decision tree, random forest, and extreme gradient boosting. The training data consist of 1000 samples, which may not be sufficient for an accurate estimation of the probability of failure.

Results: As a result, the surrogate models are able to predict with high accuracy the horizontal displacement at the slope toe at different time steps caused by rainfall infiltration. Based on the predictions of the surrogate models on a much larger dataset, one million sample values, the probability of failure is determined for several time steps after rainfall. Due to the effect of rainfall infiltration, the probability of failure increases with time. However, the presence of vegetation delays slope instability as a consequence of the increased soil shear strength.

Conclusions: Among the surrogate models tested, extreme gradient boosting shows the best predictive performance with an average coefficient of determination R2 higher than 97%. The reduction in calculation time demonstrates that intelligent surrogate models are a powerful tool to overcome the computational effort of Monte Carlo simulations. Furthermore, the implementation of machine learning algorithms allows for the successful integration of probabilistic approaches with sophisticated coupled hydro-mechanical deterministic models.

CONTRIBUTION OF SLOPING OLIVE YARDS TO SLOPE STABILITY: PRELIMINARY RESULTS

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Purpose: Olive yards are widespread all over the Mediterranean region, with local extra zonal presence also in hilly areas of northern Italian Apennines as supplementary cultivation in territories vocated to other cultivations, as grapevines and cereals. In hilly sector of Oltrepò Pavese area (Lombardia region), historical evidences and current local implants testify a potential vocation of some sectors of this territory to olive cultivation. The rising air temperature and the decrease in the probability of occurrence of cold days, due to climate change, may increase the actual and the future vocation of this territory to olive cultivation, also as a supplementary plant for integrating the typical vineyards present in this area. Cultivated hillslopes of Oltrepò Pavese are also very prone to rainfall-induced shallow landslides, which cause several damages to cultivations and the loss of fertile soils. In a view of future diffusion of olive cultivation in this area, it becomes fundamental evaluating the contribution of olive plants to shallow slope stability, to determine if this cultivation could help in reducing the susceptibility towards shallow slope failures. In this framework, the preliminary results of a research aiming to quantify the contribution to slope stability made by olive plants by the root mechanical reinforcement are presented.

Methods: In some test olive yards of Oltrepò Pavese, root density was measured and used as input to estimate root mechanical reinforcement through Root Bundle Model approach, in soil layers at different depths. Root density and reinforcement were correlated to different olive yards features and soil properties, to identify potential patterns influencing olive root impacts to slope stability. The estimated range of olive root reinforcement was, then, inserted in probablistic simplified slope stability model, in order to assess the probability of occurrence of shallow slope failures for cultivated olive yards in correspondence of different slope steepness.

Results: Root reinforcement of olive plants at different depths were retrieved and inserted in the probabilistic model to obtain a probability of rupture for different slope steepness. These results were compared to other typical land uses of the study area (e.g. vineyards, woodlands, sowed fields, shrub lands) in terms of comparison of the potential effectiveness of olive yards in the reduction of landslides susceptibility, highlighting ranges of slope steepness for which olive yards may give a positive contribution to slope stability.

Conclusions: These preliminary results will contribute in more detailed analyses on the possible land use managements acting as mitigation measures for shallow landslides. The present work was in the frame of OLIO project, funded by GAL Oltrepò Pavese.

EFFECTS OF MIXED-PLANTING CONDITION ON STABILITY OF A THREE-DIMENSIONAL VEGETATED SLOPE

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Purpose: Under a changing climate, extreme rainfalls happen more frequently and threaten slope safety. Soil bioengineering using vegetation is an environmentally friendly way to stabilise slopes on account of its hydrological and mechanical reinforcement. Moreover, mixed plant species of different functional groups (e.g., tree and grass) are often found in the field, instead of one, as illustrated in Figure 1. Ecological engineers who adopt soil bioengineering technique would want to, on one hand, enhance the slope stability and on the other hand to grow multiple species for maximising ecological restoration effects. Previous studies on vegetated slope stability only focus on single species. Furthermore, the existing modelling approach of root hydro-mechanical reinforcement mainly suits grass instead of spatially planted trees with tap roots, much less for mixed-planting conditions. Hence, it is essential to develop a novel modelling approach for analysing the stability of three-dimensional (3D) vegetated slopes considering various root systems. Besides, the effects of mixed grass-tree conditions on both hydrological and mechanical reinforcements are necessary to be investigated for soil bioengineering applications.

Methods: This presentation proposes a novel 3D theoretical model describing the effects of hydro-mechanical reinforcement of root systems on the stability of initially unsaturated soil slopes, as shown in Figure 1. Primary and secondary roots are differentiated within the root system. Root water uptake is modelled using the root-soil interaction approach at the microscope scale. The model considers (a) the suction difference between soil and roots, (b) root axial and radial permeability, and (c) the water uptake reduction factor. Regarding root mechanical reinforcement, the model accounts for pull-out failure as well as tensile failure for primary roots while mainly considering tensile failure for secondary roots. The 3D theoretical model with hydraulic considerations is implemented using the finite element method, while reinforced slope stability analysis is conducted using the limit equilibrium method. The proposed model is then validated with the previous centrifuge test. Three series of numerical simulations (namely grass-only, tree-only, and mixed grass-tree) are carried out to investigate the effects of mixed-planting conditions on the stability of a three-dimensional vegetated slope subjected to 100-year extreme rainfall. Different tree spacings are also considered to study grass-tree hydraulic interactions.

Results: The model predictions are compared with the measured results from centrifuge tests for model validation. It reveals that the proposed new theoretical model can capture the influence of plant roots on 3D pore water pressure distributions during both transpiration and rainfall. Then, the computed results from parametric studies are discussed regarding inter-species competition for soil water, pore water pressure distribution and factor of safety. The minimum factor of safety from design guidelines of earth slope is also involved in the comparison.

Conclusions: The novel approach proposed in this study is capable to analyse the hydrological response and slope stability of a three-dimensional vegetated slope under mixed-planting conditions. The design recommendations on planting strategy are provided for vegetated slopes subjected to 100-year extreme rainfall.

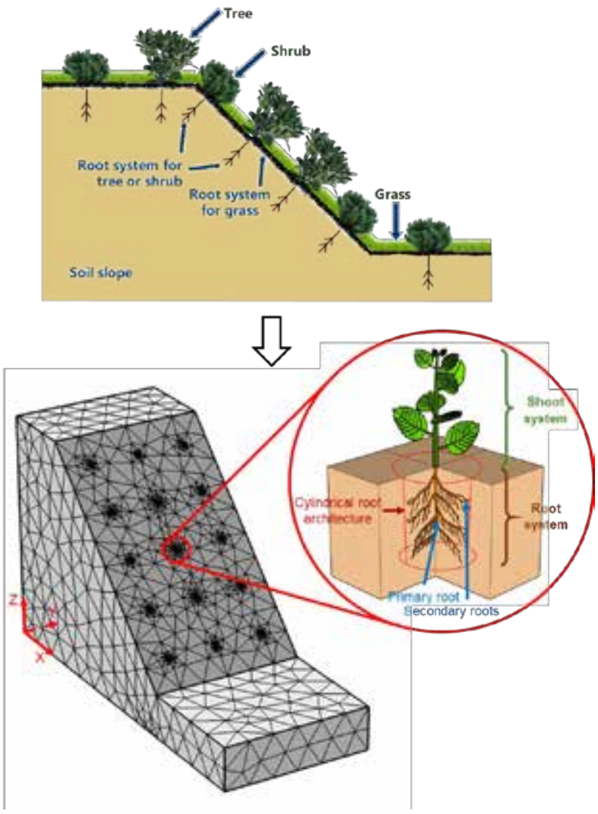

Fig. 1: Schematic diagram of a typical 3D vegetated slope under mixed planting conditions.

COMPARISON BETWEEN SLIDEFORMAP AND SHALSTAB SHALLOW LANDSLIDES SUSCEPTIBILITY MODELS: THE GARFAGNANA (NORTHERN TUSCANY, ITALY) CASE STUDY

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Purpose: Shallow landslides are complex mass movements that can be the cause of high risks in mountainous regions when intersecting infrastructures and residential areas. These processes are often triggered by intense rainfall events and, due to high frequency, high propagation velocity and lack of warning signs, represent one of the most dangerous and destructive hazards in the world. The modeling of these phenomena is particularly difficult but fundamental for an integrated mitigation of risks. In view of this motivation, several modelling approaches have been developed in the past, of both deterministic and probabilistic types. In most of the current shallow landslide modelling tools, root reinforcement is generally implemented in a simplified way, for example by including homogeneous root reinforcement (SHALSTAB) (Disperati et al., 2018). On the contrary, very few models (SlideforMAP) (van Zadelhoff et al., 2022) consider different forest spatial properties (e.g. forest structure, tree species, and different root reinforcement mechanisms). Therefore, our research is aimed at investigating the impact of different approaches for root reinforcement contribution on the prediction of shallow landslides at regional scale.

Methods: A study area was chosen in the Garfagnana basin (Northern Tuscany, Italy), where vegetational and engineering geological data were collected in the field (about 150 trenches). Acquisition of data within landslide areas was supported by means of a multi-temporal landslide inventory already available (D'Addario, 2021). Both deterministic finite-slope (SHALSTAB) and probabilistic 3-dimentional (SlideforMAP) approaches were implemented to assess and compare shallow landslide susceptibility maps for the study area, as well as to analyze the role of spatial distribution of above and below-ground vegetation features.

Results: Vegetation data obtained from field survey highlight a spatial variability of below-ground data that does not appear to match with the above-ground data. Results in terms of root-related cohesion seem consistent with values previously reported in the literature. The analysis of the susceptibility scenarios show that the bedrock geology controls the quality of the outputs from both models, with lower reliability resulting for carbonate bedrock areas.

Conclusions: Results of both models highlight that the implementation of the vegetation effects, especially root reinforcement, while providing new relevant input information, also represents an additional challenge for modelers due to its high spatial variability.

SESSION 2.10

SOIL MOISTURE AND RAINFALL MEASURED THROUGH REMOTE SENSING FOR MONITORING AND PREDICTING LANDSLIDES

DIELECTRIC SPECTRUM ANALYSIS OF SOILS DUE TO DRYING-WETTING RATE AND ENVIRONMENT INFLUENCES USING TDR PRESSURE PLATE

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Purpose: Shallow landslide is one of the natural disasters that arise on slope land. This kind of landslide, which generally occurs on slopes with residual soils overlying bedrock, is often caused by infiltration of rainfall, changing the water content of the unsaturated soil. Hence, monitoring the water content and characteristic of the unsaturated soil layer on the slope is necessary. Therefore, Time Domain Reflectometry (TDR) is utilized to measure the soil moisture content and electrical conductivity (EC)/resistivity to address the problem. The result of dielectric spectrum analysis of soil from full inversion analysis and phase velocity method fit greatly, especially at the 0.1 GHz to 1 GHz frequency range. The result indicates that the dielectric spectrum of soil with a higher drying rate will have a higher difference between each cycle than soil with a lower drying rate.

Methods: Time-domain reflectometry (TDR) is a technique used to measure the moisture content of soils, and it can be used to monitor shallow landslides by providing information on changes in soil moisture content that can trigger instability. TDR works by sending an electromagnetic pulse through a waveguide inserted into the soil. The pulse travels through the soil and is reflected back to the waveguide when it encounters a change in dielectric permittivity, which is related to changes in soil moisture content. By measuring the time delay between the transmitted and reflected pulses, the distance to the point of reflection is determined, which corresponds to the moisture content of the soil at that depth. The current study involves TDR to retrieve the dielectric spectrum of soil from the TDR Pressure Plate device with a low wetting and drying rate. The soil red clay soil of National Central University with different dry density such as 1.35 g/cm3 and 1.45 g/cm3 was employed to investigate the effect of various salinity (100-700 µS/cm) and pH values (5-7).

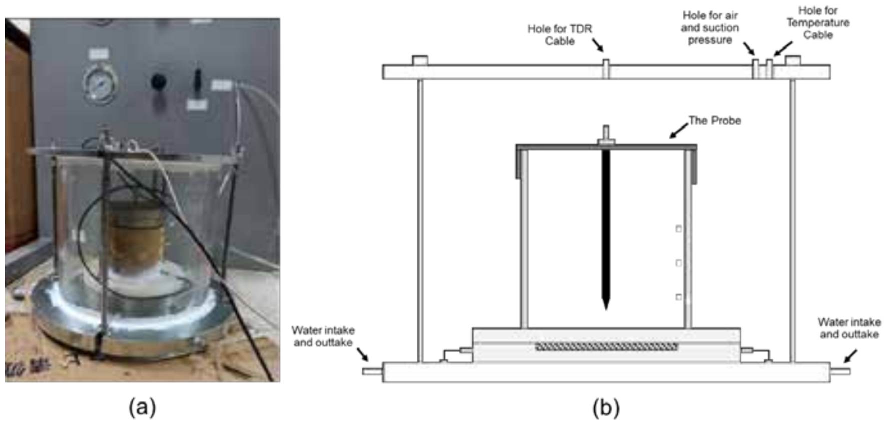

Fig. 1: (a), (b) The chamber and TDR probe setting and chamber.

Results: Figure 2 shows the test result for sample 1 with 1.35 dry density and 12.6% initial gravimetric water content with 164.5 S/cm conductivity of water. The test began by wetting the soil sample with water and stops after the soil sample is fully saturated or the degree of saturation reaches 1.00. Figure 3 illustrates the relationship of EC and volumetric water content. Similarly, figure 4 illustrates the dielectric spectrum of the sample accordingly.

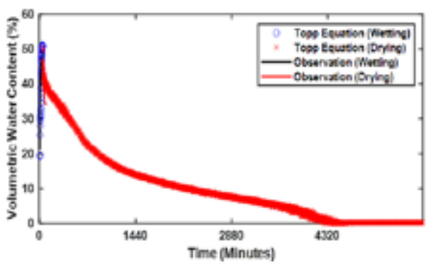

Fig. 2: The drying process in the first cycle for sample 1.

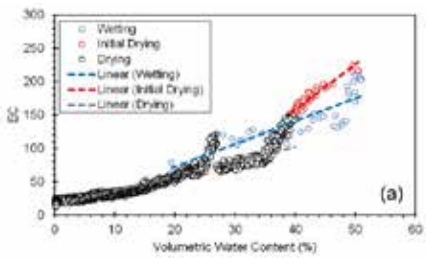

Fig. 3: EC vs θ for each process of sample 1.

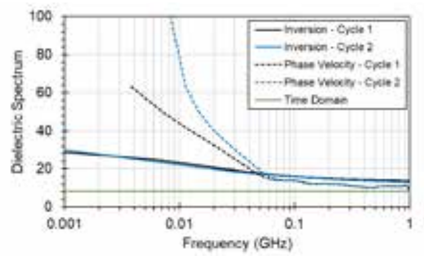

Fig. 4: Dielectric spectrum.

Conclusions: Based on the experimental investigation it has been concluded that, TDR can be a useful tool for monitoring shallow landslides because it provides real-time information on changes in soil moisture content that can lead to instability, allowing for early warning and mitigation measures to be put in place.

COMPARISON OF DIFFERENT RADAR-RAINGAUGE PRECIPITATION-MERGING-METHODS FOR THE TUSCANY REGION

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Radar-based rainfall estimation is a useful tool for processes monitoring from remote, in domaines including hydrological and environmental modelling, until applied geomorphology and landslides. However, such data may include systemic and natural perturbations that need to be corrected before using these data. To encompass this problem, adjustments based on raingauge observations are frequently adopted. In this research, we compared the performance of different radar-raingauge merging procedures on a regional raingauge-radar network focusing on a selected number of rainfalls events.

The methods we studied are of 1) Kriging with External Drift (KED) interpolation (Wackernagel 1998), 2) Probability-Matching-Method (PMM, Rosenfeld et al., 1994), and 3) an Adjusted kriging mixed method exploiting the conditional merging (ADj) process (Sinclair-Pegram, 2005). The latter was made available by DPCN (Italian National Civil Protection Department), while methods 1) and 2) were applied on recorded raingauge rainfalls over the Tuscany Regional Territory at 15' time-step, and CAPPI (Constant Altitude Plan Position Indicator) reflectivity data from the Italian radar network at 2000/3000/5000 m at 5' and 10'. Relationships describing precipitation VS radar reflectivity were integrated and analysed as part of the development of the merging procedures. The comparisons between the three rainfall fields were based on the analyses of variance, Cumulative Distribution Function (CDF), and explicative coefficients such as BIAS, RMSE (Root Mean Square Error), MAD (Median Absolute Deviation).

In general, average rainfalls showed slight variability between the methods. Comparing CDFs, little differences were detected between KED and ADj with bias mostly pronounced in lower quantiles, while more marked differences are observed in higher quantiles for the ADj-PMM methods. The analyses showed different precipitation spatial patterns depending on the applied procedure, closer to the radar data when using ADj, and more reflecting the gauge's data structure when adopting KED. The probabilistic method (PMM) had the advantage to account for gauge data while preserving the spatial radar patterns, thus confirming interesting perspectives.

Comparing the performance of different radar-raingauge merging methodologies was useful in order to better understand the specificity of the available radar-data-elaborations at the regional scale that can be adopted for modelling procedures. It was possible to obtain a clearer picture of which methodology is the most suitable in terms of spatial and temporal representativeness, variance, and image patterns.

EARLY WARNING OF SHALLOW LANDSLIDE ON SOIL MOISTURE IN GUIZHOU PROVINCE, CHINA

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Purpose: From 2016 to 2020, 149 shallow landslides were triggered in Guizhou Province, China causing significant economic losses and casualties. Early warning of the occurrence of shallow landslides in Guizhou province can reduce casualties.

Methods: The calculation method of soil surface moisture obtained through remote sensing and meteorological data can be used for the determination of soil moisture through rainfall. There are 85 shallow landslides events with detail rainfall data and triggered time during 2016 and 2020 in Guizhou Province. The early-warning model of shallow landslide in Guizhou Province, China was established based on the rainfall and soil surface moisture, rainfall duration and average rainfall intensity of these landslide events. During the same period, there are 64 shallow landslides events with detail rainfall data, but without detail triggered time in Guizhou Province. The early-warning model was verified by these landslide events.

Results: The results show that the triggering rainfall of shallow landslide in Guizhou Province is least moderate rainfall, and its soil moisture is always above 0.37. The determination method of triggering rainfall based on soil moisture is to determine the rainfall duration of triggerring landslide (D=1h) from the first hour when the soil moisture is 0.37 or above. When the soil moisture is less than 0.37, the rainfall is set to end, and the influence of previous rainfall on potential landslide is no longer considered. After the first hour of rainfall is determined, the early warning model of shallow soil landslide in Guizhou province based on ID model is established by the rainfall data and triggered time of landslides: ID0.894>Cr, where I is the average rainfall intensity (mm/h), D is the rainfall duration (h), Cr is the critical values, = 32.6, 61.7, 90.8, respectively. The possibility of landslide occurrence is divided into: The probability of occurrence is low (<32.6), the probability of occurrence is medium (≥32.6, and <61.7), the probability of occurrence is high (≥61.7, and <90.8), and the probability of occurrence is very high (≥90.8).

Conclusions: The rainfall that triggers shallow landslide in Guizhou province is generally a relatively long-time heavy rainfall or rainstorm, or a relatively short time rainstorm or large rainstorm, or even an extraordinary rainstorm. On the basis of 24h moderate rainfall (soil moisture above 0.37), extremely short duration rainstorm or short to medium duration heavy rainfall may trigger shallow landslide in Guizhou Province, China and the corresponding rainfall duration is within 3-64h. The prediction model in this study can well predict the occurrence of shallow landslides and can be used for landslide warning in Guizhou Province.

RANDOM FOREST MODEL AND GRIDDED PRECIPITATION PRODUCTS APPLIED TO LANDSLIDES FORECASTING IN THE COLOMBIAN ANDEAN REGION

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Purpose: The Colombian Andean Region has been associated with rain-triggered landslides over time due to its high topographic gradients and climatic conditions; for this reason, the definition of rainfall conditions that trigger landslides has been a great interest study area. However, many areas that compose this region need terrestrial rainfall gauges to relate rainfall to landslides; in this sense, the information provided by satellite rainfall databases is a tool to address this deficiency. This work focuses on determining landslide occurrence probabilities in the Colombian Andean Region using the machine learning classification model: Random Forest, implementing rainfall variables and landslide conditioning factors for the period of the landslide inventory (1981-2019).

Methods: In this work, we used ground-rainfall data from the Colombian Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) gauges and two gridded precipitation products: The Climate Hazards Group Infrared Precipitation with Stations (CHIRPSv2) and the multi-source weighted-ensemble precipitation (MSWEPv2.6). Subsequently, these satellite databases were used to evaluate the model's predictive capacity for rain-triggered landslides. In addition, we assessed the predictive capability of the trained model to forecast landslides using information from events outside the training period (2020-2021).

Results: The results show that the Random Forest Model is adequate and has a good predictive performance for landslide occurrence, being sufficient to obtain good predictions using only variables related to rainfall. The results also indicated that the CHIRPSv2 database is the best-performing satellite database for landslide prediction in the Colombian Andean Region, which may be a suitable option in areas where terrestrial data may be scarce, and there are drawbacks to the recorded data.

Conclusions: Finally, the pilot test of the landslide forecast model with data outside the training period (Figure 1) performed well in predicting high probabilities of landslide occurrence in the zones of interest, which confirms that the Random Forest Model is capable of predicting rain-triggered landslides and could be implemented in Early Warning Systems.

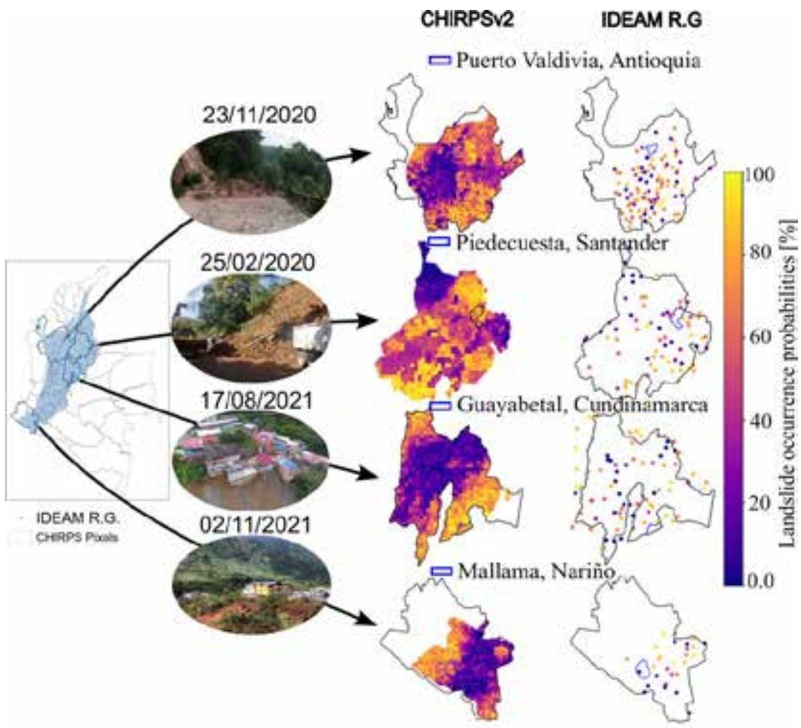

Fig. 1: Location of the areas used for the validation and the failure probabilities determined using the Random Forest classifier model: Puerto Valdivia, Antioquia, Piedecuesta, Santander, Guayabetal, Cundinamarca, and Mallama, Nariño.

INTEGRATING RAINFALL AND SOIL MOISTURE MEASUREMENTS TO ASSESS LANDSLIDE RISK ALONG HIGHWAYS

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Purpose: Landslides along highways pose a significant hazard to motorists and can lead to traffic disruptions and delays. Commonly, these unstable areas are identified based on reports of roadway distress from maintenance personnel or complaints from motorists. Once an unstable region is identified, the suspected slide area is often instrumented with inclinometers or survey monuments, which are then read at regular intervals to identify the slide plane and any changes in behavior. This reactive approach to monitoring can be effective at sites with a history of movement but can only be applied to sites that have already moved enough to lead to visible signs of distress. We are working to implement a proactive monitoring program to assess potentially unstable areas along highways in Alabama, USA. Our goal is to integrate both remote sensing-based rainfall and soil moisture measurements to identify areas where landslides are likely to occur, allowing preventative maintenance to be prioritized.

Methods: We have collected inclinometer and monitoring well data from over 40 landslide sites along highways in Alabama with reports from more than 160 landslides that occurred between 2004 and 2015 and were attributed to a specific storm event. Some sites have been monitored for more than 10 years allowing us to assess changes in the rate of movement over time. We processed the inclinometer data to define triggering events based on different threshold levels based on the severity of the movement. Similarly, the landslides without monitoring data were binned based on the observed damage to identify the severity. We then used multiple sources of rainfall and soil moisture data to trends and develop correlations with the observed movements.

Results: Our results show that precipitation magnitude and duration alone were not sufficient to predict which storm events would lead to increased movements, even when antecedent rainfall was considered. Integrating soil moisture data allowed for better differentiation between large storm events that were likely to increase the rate of movements and those that were not. These data are now being used to develop warning thresholds that can highlight areas where landslides are likely to occur. This results are being incorporated into a web portal to allow for clear communication with transportation personnel and other stakeholders.

Conclusions: Landslides along highways pose a significant challenge for both transportation officials and risk for the traveling public. Landslides lead to both direct repair costs and indirect costs associated with traffic delays and road closures. Identifying potentially unstable areas before large movements occur can allow for inspections and preventative maintenance to be prioritized in these areas. In this study, landslide observations from more than 40 monitored sites and 160 individual landslides were analyzed to identify correlations with remote sensing-based rainfall and soil moisture data. Our work has found that predictions are improved by combining soil moisture measurements with rainfall data, rather than relying on rainfall alone. The results of the study can be used to identify areas along highways where landslides are likely to occur allowing time for transportation officials to intervene.

ASSESSING THE POTENTIAL OF DIFFERENT SATELLITE SOIL MOISTURE PRODUCTS IN LANDSLIDE HAZARD ASSESSMENT

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Purpose: With the development of remote sensing technology, satellite-based soil moisture estimates become more and more available, and the potential of using satellite soil moisture products in landslide hazard assessment has been widely recognized. However, to our knowledge, there is a lack of studies exploring the performance difference of various satellite soil moisture products for such an application. Therefore, this study aims to compare several state-of-the-art satellite soil moisture products on their potentials in landslide applications.

Methods: The selected products include the ESA CCI soil moisture dataset, the SMAP Level-3 (L3), enhanced Level-3 (L3), Level-4 (L4) surface, and Level-4 (L4) root zone soil moisture datasets. Specifically, the completeness of different datasets is calculated to assess their applicability in practical applications. To investigate the relationship between the soil moisture and the commonly used rainfall information in landslide predictions, the correlation study of the satellite soil moisture with the antecedent cumulated rainfall is also carried out. In addition, to explore whether the satellite soil moisture can provide valuable information for landslide hazard assessment, infiltration events are identified based on the time series of satellite soil moisture, and the significance of event characteristics (such as event duration, soil moisture change, etc.) in landslide occurrence is then investigated with Bayesian analysis. This study is carried out in a landslide-prone area, the Emilia-Romagna region in northern Italy.

Results: Results show that the SMAP L4 product does not have any missing values, beneficial to the continuous monitoring of landslides. As for the correlation relationship between soil moisture and antecedent cumulated rainfall, the SMAP L4 product also has more rational spatial distribution of the Pearson correlation coefficients compared with other datasets, which can be better explained by the distribution of slope and TWI (topographic wetness index). Bayesian analysis on the infiltration events shows that our prior knowledge of the probability of landslide occurrence is better improved by using the 'SMAP L4 root zone soil moisture'-derived infiltration events.

Conclusions: It can be concluded that the SMAP L4 root zone soil moisture has a greater potential to be used for landslide hazard assessment in the study area.

IDENTIFYING HYDROCLIMATIC PRECURSORS FOR SUDDEN ACTIVITY TRANSITIONS IN LARGE LANDSLIDES USING MODELLED HYDROCLIMATIC DATA FROM SATELLITES

Richard Carter[1], Corey Froese[2], Corey Scheip[1], Michael Porter[1], Geoff Eichhorn[3], Dave Gauthier[1]
[1]BGC Engineering, [2]Wavelength Advisory Services, [3]Royal Military College of Canada

Purpose: One aspect of managing risk from landslides along linear infrastructure corridors includes forecasting precipitation trigger events that may influence soil slope stability. This requires an understanding of the regional correlation between landslide activity and antecedent precipitation and soil moisture conditions at the time of landslide initiation or re-activation. This correlation can be accomplished at the site-level by means of in-situ instrumentation collecting time series data representing ground movement and hydroclimatic inputs such as soil moisture, temperature, and precipitation. However, this type of instrumentation is not a practical solution at the regional-scale given the cost and effort required to collect enough data to make meaningful correlations between these variables at the regional scale. Until recently, antecedent precipitation has been used as a proxy for soil moisture given its relative ease to measure and track over time and space. More recently, modelled hydroclimatic time-series data with continuous spatial coverage provide a potential alternative and/or supplement to precipitation data for the study of landslide behavior in that it is able to provide data representing multiple hydroclimatic inputs (e.g., soil moisture).

Methods: As part of a project initiated in Western Canada, a global hydroclimatic model (ERA-5) developed by the European Centre for Medium Range Weather Forecasting was utilized to assess how multi-year fluctuations in soil moisture and precipitation correlated with the timing of episodic ground movement at known landslide locations with in-situ instrumentation measuring displacement. In this study, we test the utility for the study of landslides of ERA-5 and similar data sets such as NASA's Moderate Resolution Imaging Spectroradiometer and Soil Moisture Active Passive by means of a number of case studies for rapid accelerations at locations across North America where no instrumentation data is available but the timing and location of rapid failure following a large precipitation event is known. Within these case studies we will also evaluate the value added by the access to soil moisture data leading up to landslide events as opposed to precipitation alone.

Results: There are two intended outcomes of this study. First, the relative strengths of the various hydroclimatic datasets noted above will be explored and demonstrated. Second, the case studies completed for this study will provide meaningful insight on how time-series hydroclimatic data can be used in a predictive manor at the regional scale.

Conclusions: This study will aim to draw conclusions on how to design and implement regional-scale landslide risk management systems which rely on modelled hydroclimatic data as a primary input.

SESSION 2.1

CASE STUDIES AND STATE OF THE ART ON LANDSLIDE MONITORING (part III)

LANDSLIDE MONITORING NETWORK IN ITALY: CURRENT STATUS AND FUTURE PERSPECTIVES

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Italian Institute for Environmental Protection and Research (ISPRA), Geological Survey of Italy, Roma, Italy

Purpose: The Disaster Risk Reduction (DRR) policies imply that landslide hazard assessments are needed for suitable risk management. To enable such assessments, landslide databases consisting of inventories, maps, and associated information (e.g., pictures, field data), represent a key infrastructure. In this framework, data from monitoring systems is crucial to a better understanding of both landslide processes and existing monitoring itself. However, monitoring data is often missing in landslide inventories also due to restrictions on data dissemination. In other cases, data is inhomogeneous and not easily comprehensible. Although the landslides surveyed in the Italian Landslide Inventory (IFFI) number more than 620,000, according to the National Register of Landslide Monitoring Systems, designed in 2021 by the Italian Institute for Environmental Protection and Research (ISPRA), about 1,222 landslides result monitored with in situ systems.

Methods: The National Register, available on the IdroGEO web platform (https://idrogeo.isprambiente.it), consists of the following information: system code, location, managing entity, installation and dismantling dates, activity, typology (knowledge/early warning), acquisition type (manual/continuous/both), webpage link, notes, instrumentation, associated landslide ID. At present, the Register contains data from 12 Regions, 2 Autonomous Provinces and from systems managed by ISPRA in 4 further Regions. Moreover, a census by 2 additional Regions is ongoing.

Results: Overall, active monitoring systems are 487 (56%) while dismantled and under construction systems are 358 (42%) and 17 (2%) respectively. Most of the systems (678; 79%) have a knowledge purpose while 184 systems (21%) are or have been also used as Early Warning Systems (EWS). Data acquisition is performed manually (665), automatically (45) or in both ways (145). The most used instruments are inclinometers and piezometers, followed by topographic instrumentation, weather stations, crack meters, strain gauges, terrestrial radar, etc.

Conclusions: Considering current data, some considerations on preliminary findings can be made. First, to achieve significant results data from all administrative levels and monitoring managers is needed. Although the number of EWS is non-negligible, there are still few monitoring systems having this purpose. Also, continuous automatic data acquisition is still not widespread and it should be improved to reduce monitoring costs and operator errors. Finally, conventional monitoring tools (e.g., inclinometers, piezometers) continue to be widely used. Within the context of the GeoSciencesIR project, funded by the Ministry of University and Research through the National Recovery and Resilience Plan – Next Generation EU and led by ISPRA, an experimental open source National Database of Landslide in situ Monitoring Systems (NDLMS) will be developed by implementing database structure, minimum information needs, data quality requirements and access policies, following international standards on data and metadata (e.g., INSPIRE), according to FAIR principles. At first, NDLMS will store data from the experimental monitoring sites of the GeoSciencesIR project. The motivation for developing this new database is twofold. First, NDLMS will be an important step towards a more comprehensive hazard framework: making the database available will enable stakeholders to know new monitoring approaches and technologies as well as to possibly implement new systems based on well-tested methodologies. Furthermore, adopting consistent data standards will be key to enabling interoperability. Secondly, a reliable and high-quality database provided to the scientific communities will represent a valuable resource to develop future data-driven studies for landslide assessment, modelling, and monitoring.

MONITORING RESULTS FOR SAFETY MANAGEMENT STRATEGY IN SILTY CLAY LANDSLIDE AREA SOUTH EAST HUA;IEN, TAIWAN AFTER HEAVY RAINFALL AND STRONG EARTHQUAKE

Lin Bing-Shyan (Ben)[1], Hui-Chi Hsu[2], Zhi-Hao Wang[3], Yu-Lin Chen[4]

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Purpose: Large scale potential landslide mitigation and monitoring has been an important job for Taiwan slope management after Typhoon Morakot. For the eastern part of Taiwan, the geology of Hai-An mountain basis of Silty Clay, therefore, underground water and surface runoff play an important roll for these landslide potential areas. This study conducts the method of surface elevation survey and continues monitoring result behavior compare to modify a disaster prevention management benchmark value for each individual site.

Methods: In this study, the usage of monitoring device such as rain gauge system, water pressure meter surface tilt meter, bore hole tilt meter, airborne UAV image DSM, InSAR images and by the usage of monitoring statistic result help analyses the mass movement detail for landslide potential areas to find out what & where is the movement is taken place. And by calculating the time interval to establish the small area shallow potential landslide prevention work and disaster prevention escape plan.

Results: From result, during 2021 October Typhoon, surface changes a lot in AnTong village, and from monitor instrument daily result, according to three different individual active mass, only at the upper and right division has sliding potential, but after 918 earthquake (M6.8) the entire area move rapidly. For LoSan village, during 2021 October Typhoon, ground water height has great influence to surface stability, and during two major scale earthquake, groundwater effect. For DianTaiSan During the Typhoon rail the entire area was under warning, and for during two different earthquake, the upper region underground water level had become highly effected, but from surface deformation result, nothing much had changed except for the upper region that makes pre-warning system more reliable by the change of.GNSS shown in Figure 1 and Table. 1.

Conclusions: From above mention, the combine use of surface deformation and monitor instrument result for daily pre-warning usage. and for secondary stage use, the acumination result for each active mass from up to low position can be abducted for different real time monitor interval, then the special result cam be related well for future warning.

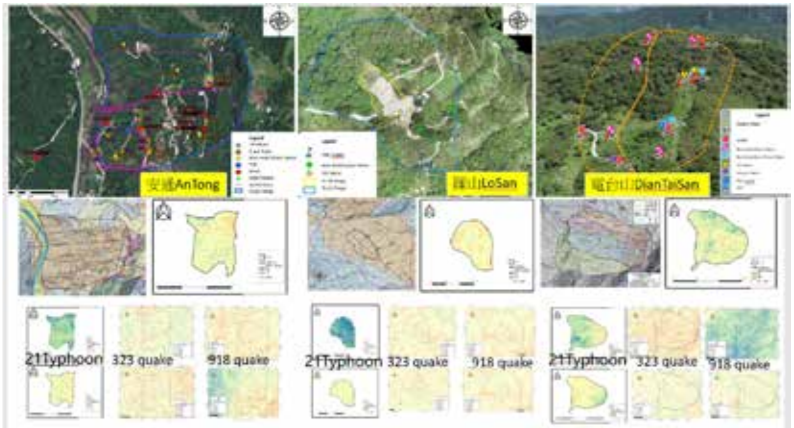

Fig. 1: Three different Landskide potential site monitor point and surface deformation result.

Table 1: Three Different Landskide potential site Monitor result of dailly event for disaster pre-warning

安通AnTong

1日	21Typhoon	323	918		21Typhoon	323	918		21Typhoon	323	918
BH8	-1.58	-7.61	-9.97	RAIN	822.5	0	0	BH3	-0.94	-6.42	-13.6
TT7	0.00	0.10	0.00	GNSS2	0.01	0.19	1.37	BH5	FULL	-0.30	-0.64
GNSS3	0.01	0.11	0.57	TT4	0.10	0.00	0.00	BH6	-2.07	-6.87	-6.70
TT6	0.10	0.10	0.10	BH4	0.1	0.70	0.60	TT3	0.10	0.00	0.10
BH9	-30.82	-38.91	-43.48	GNSS1	0.01	0.02	0.94	BH7	-3.91	-5.94	-6.33
GNSS4	-	-	1.08	TT!	0.00	0.60	0.20				

羅山LoSan

1日	21Typhoon	323	918
LUS	929	0	0
BH-1	FULL	-4.88	-7.24
BH-6	FULL	-0.89	-2.19
LH-4	1.6	0	0.2

電台山DianTaiSan

1日	21Typh	323	918	1日	21Typh	323	918
RAIN	845	0	0	GNSS1	NA	NA	0.456
TH5	5.43	0	0	TH2	3.57	-0.021	0.032
GNSS2	NA	NA	0.531	EL1	0.1	0	0
TH6	3.21	0.007	0,014	EL2	0.4	0	0.1
GNSS3	NA	NA	0.348	TH3	2.72	-0.24	1.1
TH7	2.21	0.026	0.72	GNSS4	NA	NA	0.543
				TH4	4.78	-0.22	1.78

FLOWSLIDES SPATIAL MODELING AND MONITORING: EXPERIENCES CARRIED OUT IN FAITO TEST FIELD (SOUTH ITALY)

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Università degli Studi di Napoli Federico II, Department of Civil Engineering and Environmental (DICEA), Naples, Italy

Purpose: Flow-like landslides represent one of the major natural hazards worldwide for the structures and the infrastructures located at foothills. These phenomena are weather-triggered events due to preparing soil humidity conditions and critical rainfalls. Although the crown area involves few cubic meters of soil, they increase in volume and velocity downslope. Campania Region (Southern Italy) is very prone to these kinds of landslides that historically produced casualties and damages. In this study the monitoring of most common soil hydraulic parameters is combined with spatial modeling of factor of safety (FS) for the slopes of a critical area.

Methods: The paper describes the geological and geotechnical characterization of the test site set up on Faito Mt. (Castellammare di Stabia, Naples province, South Italy). It is located in an area affected by historical flowslides, the last one occurred in 1997. It consisted of a digital elevation model DEM (1x1 m) obtained from a Lidar survey; 21 stratigraphic logs reaching a maximum depth of 4 m obtained from hand-made boreholes and trenches; 45 soil samples taken for grain size classification and physical property definition; 27 undisturbed soil samples collected to perform saturated permeability tests at a constant head; 9 ERT profiles for defining the electrostratigraphy of the cover and the physical and morphological conditions of the bedrock. Conversely, the monitoring equipment was made of 40 tensiometers and 42 TDR probes in 10 verticals installed at different depths to measure the soil suction and volumetric water content until a maximum of 2.8 m depth. Finally, one weather station was also installed, it is constituted by a rain gauge, a radiometer, an air thermometer and an air humidity sensor to study water infiltration and evapotranspiration. The study of slope stability was attained calculating the Factor of Safety (FS) at the scale of the slope with the Limit Equilibrium Method (LEM). The depth of the potential shear surface was assumed at the base of the shallower soil horizons. In this way spatially distributed stability analyses were performed also accounting for the recorded value of soil suction and volumetric water content.

Results: The performed activities allowed us to reconstruct the spatial distribution of FS at the scale of the slope and to account for the recorded values of both suction and volumetric water content in the area. The study was indirectly validated by the occurrence of small flowslides in the neighboring of the site. They occurred when in the site the lowest value of soil suction were measured, while the worst-case scenario (where FS is less than 1) is attained with the complete saturation of the soil horizons.

Conclusions: This study permitted to set up an experimental site in an area characterized by a high flowslide risk. The spatial modeling of slope stability joined with the monitoring of the main soil hydraulic parameters represents an asset for implementing early warning strategies.

CHARACTERIZATION AND MONITORING OF URBAN LANDSLIDE HAZARDS USING GEOPHYSICS, REMOTE SENSING, AND WIRELESS SENSOR NETWORKS

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Lawrence Berkeley National Laboratory, Berkeley, United States

Purpose: Growing urbanization is pushing communities further into areas of known landslide hazard, elevating the risk posed to these communities. Hence, there is an increasing need to develop approaches that can characterize and monitor landslide hazards in urban areas. Here, we present the characterization of the landslide hazard at a highly developed site in the Berkeley Hills, CA, and focus on the development and results of a wireless sensor network installed at this site.

Methods: The python-based hydro-geomechanical model Landlab is used for a geostatistical evaluation of the landslide hazard. Testing the sensitivity of the model showed that the parameters influencing the results most are the slope gradient, soil thickness, and total cohesion. The slope gradient was calculated from LiDAR data, and the soil thickness estimated from both intrusive investigations and ambient seismic noise (horizontal-to-vertical spectral ratio) measurements. To estimate the total cohesion, we classified optical remote sensing data to obtain a vegetation distribution, which we used to estimate the root cohesion. Other parameters, such as friction angle, or precipitation input, are taken from geotechnical investigation and weather records. A wireless sensor network employing soil moisture/ pore pressure and deformation sensors was installed with a focus on areas of high landslide hazard. The deformation sensors were developed at Berkeley Lab and make use of an array of accelerometers. Sensors are connected using novel communication protocols that allow for ultra-low-power consumption.

Results: The landslide hazard assessment shows areas of elevated landslide probability in areas of thick soil cover and steep slope angle. This is mostly the case in the eastern and northwestern part of the study site, where landslides are frequently observed. Lab tests of the deformation sensor show an accuracy of 2 mm/m. Across the study site, triggered by a number of storms, we observe deformations of up to 7 cm that correlate in time with a rise in soil moisture content and pore pressure. Using machine learning, we use this data to predict subsurface conditions critical to slope failure. We show that short-term predictions are comparably accurate, while long-term forecasts fail to predict sudden changes, mostly due to a lack of training data. The hazard assessment and data obtained from the sensor network are starting to be incorporated into site management with the aim to mitigate the landslide risk

Conclusions: Here we show how we can use remote sensing and geophysical data to parametrize a hydro-geomechanical model to assess the landslide probability of a highly developed urban site. We show that vegetation has a considerable influence on the landslide hazard and that site management has to act appropriately. Developments in sensor design and data communication allowed us to operate a wireless sensor network comprising more than 75 locations where we measure soil deformation and soil moisture/pore pressure. This data has proven useful in mitigation of the landslide hazard, and developments in machine learning show that short-term and perhaps long-term predictions for landslide early warning are possible.

MONITORING LANDSLIDE INSTABILITY: A CASE STUDY OF MOUNT AMIATA VOLCANIC COMPLEX, ITALY

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Purpose: Landslides are a significant hazard that poses a threat to infrastructure, property, and human lives. Monitoring is crucial for early warning, risk assessment, and mitigation measures. This study discusses the implementation of an integrated monitoring system for active landslides in the Abbadia San Salvatore town (eastern slope of Mount Amiata, Tuscany, Italy) causing infrastructure damages.

Methods: The integrated monitoring system utilizes a variety of surface and subsurface measurement techniques, including InSAR persistent scatterer (PS) with Sentinel-1A and 1B data, topographic surveys using leveling and robotic total stations (TS), geodetic surveys with GNSS, Time Domain Reflectometers (TDR), and inclinometers. The results from different techniques are integrated to ensure the robustness of results as well as to assess the coherence of the system by comparing the surface and subsurface displacement vector results based on the spatial and temporal resolution of the data.

Results: The measurements from the different techniques provided reasonably coherent results in terms of both magnitude and direction of displacement vectors. The InSAR results highlighted a cluster of PS to the north of the Abbadia San Salvatore town with Line-of-Sight velocities ranging from a few mm/y to 25 mm/y, with a standard deviation of less than 3mm/year. However, no PS were obtained due to thick woods, where possible landslide escarpment deformation was recognized in the field. The surface measurements provided local displacement vectors with velocities ranging from 80 mm/y in the planimetric direction (GNSS and TS) to -60 mm/y in the vertical direction (TS and leveling), with standard deviations of approximately 1 mm and 5 mm, respectively. From the TS, leveling, and GNSS measurements, a set of 3D velocity vector was calculated which allowed us to observe vector slopes varying in agreement with the local morphology. The inclinometer measurements indicated that an active sliding zone at a depth of ca. 16 - 19 meters was identified, with maximum planimetric velocities of approximately 80 mm/y. The TDR measurements are in good agreement highlighting similar depth of the shear surface. These data and the spatial distribution of the 3D vectors slope suggest a curvilinear shape for the upper zone of the landslide shear surface.

Conclusions: The integration of different surface and subsurface measuring systems allowed for the monitoring of the active landslide process in the Abbadia San Salvatore, also providing insights into the geometry of the slope instability processes. The availability of data from different systems provided useful information whereas the other system has limitations. This system is currently supporting local authorities in understanding the kinematics of the landslides and assessing the evolution over time, aiding in decision-making regarding mitigation works.

THE SAN NICOLA LANDSLIDE EXPERIMENTAL FIELD

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Purpose: The San Nicola landslide is one of the historical moving geosite landslide (sensu Calcaterra et al., 2014), affecting the UNESCO Cilento Geopark area (Campania region, southern Italy). The latest paroxysmal reactivation dates back to October 1963 after heavy rainfalls, but several precursory phenomena happened during the two years before (Guida et al., 1981). Such reactivation was the consequence of a lateral spread of sandy conglomerates over structurally-complex clayey flysch deposits, which turn out into rotational slides and earthflows. The latter destroyed portions of the old San Nicola village which was later relocated according to Central Government decisions. The occurred landslide system (sensu Valiante et al., 2021) is still evolving in a deep lateral spread and shallow slide-flows threatening the main access road and the new San Nicola village. In order to gather information useful for decision-making and countermeasure design, monitoring activities of the landslides system have been implemented since early 2021 by using conventional and innovative sensors.

Methods: The former includes 5 piezometers and 3 inclinometers, whereas the latter have been coupled with New Smart Hybrid Transducers (NSHT) (Minutolo et al., 2020). NSHT is a strain transducer based on optical fiber sensing technology suitable for real-time monitoring over long distances and, as such, it has been exploited as a smart inclinometer. Furthermore, environmental factors are monitored through a series of sensors such as a weather station and electrical piezometers, which are linked together in a digital system of data ingestion having basic pre-processing functions also capable to generate alarms if threshold values of relevant parameters are exceeded. Processed data are then sent to a cloud-based data storage system and a real-time web-based dashboard.

Results: After more than a year of monitoring activities, data density allowed for an in-depth characterization of the landslide system such as, for example, the aquifer response to precipitations or the recognition of buried sliding surfaces with different depths.

Conclusions: The results up to now obtained show the reliability of the exploited technologies given their capability of continuous measurements and real-time data handling.

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WHAT CAUSES CREEP BURSTS IN THE ÅKNES LANDSLIDE, NORWAY?

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Purpose: Slow creeping landslides move at rates of millimeters to several meters per year. They can cause extensive damage to infrastructure and pose a major threat to human lives if failing catastrophically. Landslides can progressively weaken over time by rock mass damage processes that may occur by constant slow creep or sudden transient slips. Eventually, damage can lead to strain localization along the basal shear plane and catastrophic failure of the landslide. Transient slip events, also called creep bursts, may induce short-term loading and hence can control landslide stability. These creep bursts correspond to short periods that can last several days where the displacement of a landslide accelerates and then decelerates. To better understand the physics of creep bursts we focus on the Åknes landslide, Norway, which is extensively instrumented. The Åknes landslide is moving at a slow slip rate of 6 cm per year, and could generate a large tsunami wave in a fjord if it would rupture catastrophically.

Methods: We compiled and analyzed extensive multi-physics data series of the Åknes landslide. We analyze continuous geodetic (10 GNSSs, inclinometer strings in 7 boreholes), seismic (seismometers at the surface and in a borehole), hydrologic (piezometer strings in boreholes) measurements over 8 years. Based on the inclinometers situated in the shear zone, we detected creep bursts in this landslide. We also detect endogenic seismic events that are classified into local micro earthquakes, tremors, avalanches and rock falls. We further analyzed the creep bursts in regards to surface displacement, micro earthquake activity and water pressure levels.

Results: Over inter annual timescales we observe seasonal fluctuations of landslide surface velocity, groundwater and seismic activity. Then focusing on short term timescales at the level of the shear zone, we detect an average frequency of 2 creep burst events per year per borehole. The magnitude of creep burst slip range between 0.5 to 2.5 mm. These creep bursts correspond to only 10 % of the total slip distance. Some creep bursts are occurring at the same time in all the boreholes. These phased events show an increased seismic activity at the depth of the shear plane and water pressure at the initiation of the transient acceleration. Most of the times creep bursts occur only in a single or few boreholes. The detected creep bursts occur all along the year, however, during winter, creep bursts correlates to an increase in ground water, while in summer they do not.

Conclusions: This extensive dataset provides the unique opportunity to study the mechanics of a landslide by comparing the local dynamics of the shear zone and the resulting displacement at the surface. We analyze these creep burst events and inspect the surface motion during these creep bursts occurring at the shear zone and provide the first analysis of this dataset in terms of landslide mechanics.

SESSION 5.1

LANDSLIDES AND CLIMATE CHANGE: PROCESSES, TRENDS, CHALLENGES AND PERSPECTIVES

ROCK FALL AND CLIMATE CHANGE: A QUANTITATIVE STUDY TO PREDICT CHANGES IN THE ROCK FALL HAZARD DUE TO CLIMATE CHANGE IN BRITISH COLUMBIA, CANADA

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Purpose: The purpose of this paper is to study the rock fall phenomenon and how the rock fall hazard is expected to change in the future decades as a consequence of climate change. In this regard, a quantitative study is done to estimate changes in rockfall monthly distribution due to climate change along a railway section in British Columbia, Canada. This paper provides a tool for decision-makers to develop risk mitigation plans and resilience strategies associated with climate change along transportation corridors exposed to rock fall hazards.

Methods: A statistical approach is used to quantify the relationship between monthly weather averages and rock fall frequencies for a section of a transportation corridor along the Fraser River in British Columbia, Canada. In this regard, circular distributions are used to find the best-fitted models to the recorded weather data in the period of 1990-2019. These models are then combined and calibrated to the recorded rock fall monthly frequency. The calibrated model is then used with input data from climatic predictions to see how rockfall distribution will be affected due to climate change in the future decades. Several climate models and Representative greenhouse gas Concentration Pathways (RCP) are used to get a better understanding of how climate change will affect rock fall hazard in the study area. Figure 1 shows the circular distributions defined for recorded weather data, and the fitted model to the rock fall data recorded in the period of 1990-2019.

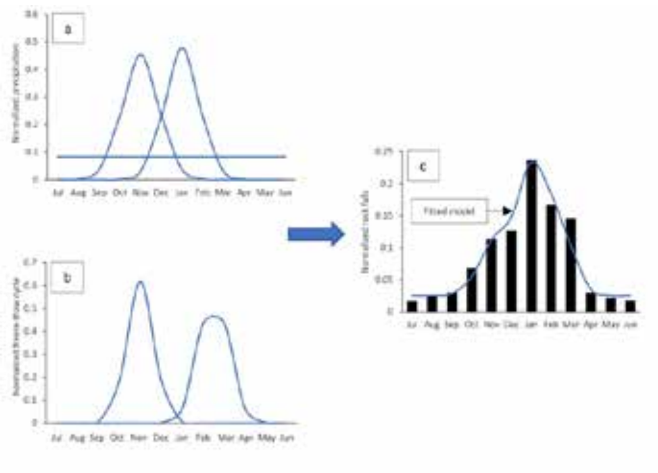

Fig. 1: Circular distributions defined for the recorded precipitation (a), Circular distributions defined for the recorded freeze-thaw cycle (b), and the model fitted to the recorded rock falls in the period of 1990-2019 (c).

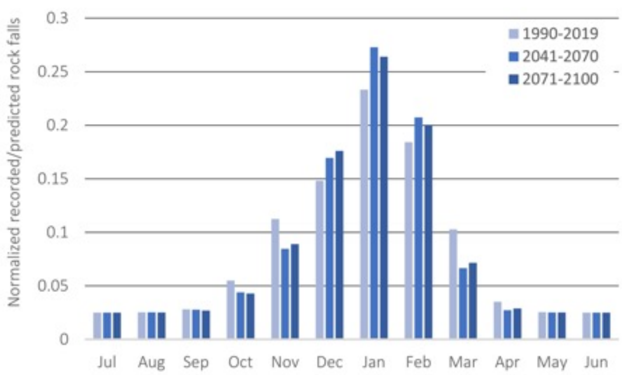

Fig. 2: Comparison between the predicted rock fall distributions due to climate change for the periods of 2041-2070, and 2071-2100 and the recorded rock fall data in the period of 1990-2019.

Results: Preliminary results show that more rockfall activity is expected in December, January, and February of each year relative to the reference period of 1990-2019. On the other hand, rockfall predictions indicate less number of events in some of the months. Based on the results, it is anticipated that the number of rockfall events decreases in October, November, March, and April. Figure 2 shows how rock fall monthly distributions are expected to change in the future decades due to climate change relative to the reference period of 1990-2019.

Conclusions: Based on the preliminary findings, new strategies for monitoring and reducing rockfall hazards can be developed in this area. Moreover, this study presents a method for quantifying changes in rockfall hazards for climate change scenarios, which will assist infrastructure authorities in prioritizing their monitoring resources for risk mitigation, as well as enhancing the resilience of transportation corridors during times of high rockfall hazards.

ANALYSIS OF SEDIMENT SOURCES AND TRANSFER DYNAMICS IN TWO CATCHMENTS OF THE LIGURIA REGION (ITALY) HIT BY STORM ALEX IN 2020

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Purpose: This work aims to understand the relationships between different hillslope instability processes triggered by a storm event, named Storm Alex, and the sediment connectivity in two mountain catchments to evaluate which process provided sediments to the valley bottoms and then to the outlets. Here, high-magnitude sediment transport took place leading to severe damage to the urban settlements.

Methods: Storm Alex occurred between 1 and 3 October 2020 and hit the Maritime Alps along north-western Italy and southern France regions, bringing up to 500 mm of rainfall in about 24 hours (Chmiel et al., 2022 https://doi.org/10.5194/nhess-22-1541-2022). For this study, two adjacent mountain catchments of the Liguria Region (northern Italy) sharing the same outlet were selected, and post-event GeoEye imagery acquired on 20 October 2020 was used to realize an inventory map of the instability processes. Images were pre-processed with the ERDAS IMAGINE® software to obtain NDVI and pansharpened color images. The two products were loaded in ArcGIS® software, version 10.7, to identify evidence of mass movements on the base of criteria adopted by geomorphologists (Fiorucci et al., 2011 https://doi.org/10.1016/j.geomorph.2011.01.013). The comparison between the GeoEye imagery with the available pre-event data, i.e., orthophotographs “AGEA 2016” and “Sentinel-2” spaceborne images, allowed identifying the processes triggered by Storm Alex. Moreover, the Index of Connectivity Map (ICM) of the two analyzed catchments was developed through the stand-alone and open source software SedInConnect 2.3 (Crema and Cavalli, 2018 https://doi.org/10.1016/j.cageo.2017.10.009). The input data required by SedInConnect consisted of: i) the DTM of the Liguria region with 5 × 5 m cell size (https://geoportal.regione.liguria.it/); ii) the weighting factor, representing a proxy of the impedance to sediment fluxes within the potential sediment linkages/pathways (Borselli et al., 2008 DOI:10.1016/j.catena.2008.07.006), that was developed by starting from the land cover map derived from the GeoEye imagery; and iii) the targets, represented in this case by the valley bottoms of the two catchments.

Results: The inventory prepared from the interpretation of the satellite images consists of 214 debris slides, 79 debris slides translating into debris flows, and 9 channels affected by concentrated flow erosion. The spatial distribution of the mapped processes was investigated based on the land cover characterizing the two catchments. The highest concentration of debris slides and debris slides/debris flows occur in the rangeland whereas channelized flow erosion prevails on bare soil. The ICM shows a pattern characterized by IC values increasing toward the valley bottoms selected as targets, where sediments tend to concentrate. The connectivity index was compared with the instability processes, based on the type of process, the geometrical size (i.e. elongation) of the features, and the distance from the targets.

Conclusions: Results show that the debris slide/debris flows are the processes most connected to the valley bottoms. This suggests that they supplied most of the sediments delivered by flooding waves to the outlet, where urban settlements experienced severe damage.

EXTREMELY SLOW LANDSLIDE RAINFALL-DISPLACEMENT RELATIONSHIPS

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Purpose: As the world's increasingly extreme weather and building conditions continue to increase the risk of landslides, the study of extremely slow processes takes a back seat to the catastrophic scale of landslides. The Carpathian Basin is an area with a low risk of landslides due to its continental climate, moderate topography and water bodies. However, along the Lake Balaton and the Danube, there are identified dangerous slopes, on which many important infrastructure lines run. Slope movements are usually caused by the soaking of strata and the increase in pressure of the water behind the zone mixed by previous movements at the foot of the slope due to precipitation. Damage incidents occur only every few years, typically without personal injury, causing unpleasant infrastructural difficulties and moderate material damage. In some of these areas, a monitoring system is in place, but even there only manual measurement is provided. It is therefore of the utmost importance to create a landslide hazard warning system that can be used to signal danger and enable intervention even without a serious instrumentation background, in view of the increasingly extreme weather conditions. We are investigating an area of the high bank at the eastern end of Lake Balaton, where there have been already more smaller movements in the 21st century.

Methods: In this area, movement and groundwater monitoring elements are installed: Casagrande piezometers and inclinometers which are measured manually about twice a week. The stability of the high bank section has been investigated on deterministic (limit equilibrium and finite equilibrium) and probabilistic basis. Using these results, the borehole logs and inclinometer displacement curves, we identified the potential shear zone along which very slow movement of the slope is observed. Thus, the rainfall and inclinometer data series provide an opportunity to investigate the delay and extent of displacement of the rainy periods. Such movements are particularly risky in the shear zone. We analyse 2-3 years of data series to identify regularities and investigate the circumstances of some past movements. The inclinometer data series are used to determine the delayed displacement response of rainy periods which result can be used without monitoring data and can be adapted to other areas.

Results: The expected result is the acceleration of slope displacement-velocity in response to a certain rainy periods in the area. The spreadsheet method includes precipitation and time factors to determine the level of movement risk. The data from the inclinometer can thus be used to verify the method and increase safety. We compare our results with international examples.

Conclusions: The development of landslide hazard warning systems is also of utmost importance in areas where monitoring is limited or impossible. The greatest risk is posed by the increasing frequency of heavy rainfall, so the method is based on the combination of rainfall, rainfall intensity, duration of the rainfall event and the preceding weather conditions.

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PREDICTION OF THE EVOLUTION OF A LARGE LANDSLIDE UNDER DIFFERENT CLIMATE SCENARIOS: A PHYSICS-BASED MODEL APPLIED TO THE RUINON LANDSLIDE (ITALIAN ALPS)

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Purpose: Large slope instability processes result from a complex interaction among geological and climatic factors. Possible variations in meteorological conditions connected to climate change may influence their evolution. Different rainfall inputs can in fact boost triggering mechanisms as well as an exacerbation of atmospheric temperatures can lead to significant induced thermo-mechanical stresses and accelerate mechanical degradation of rock masses. In this work, a multi-coupling method to predict stability and velocity of a landslide was applied by analyzing the cause-effect link between external forcing and its internal response, through a 1D thermo-poro-mechanical mathematical model of the sliding surface. After validating the model reproducing the past landslide behavior, different evolution scenarios were assessed based on future climatic projections. The analysis is applied to the Ruinon Landslide located in the Central Italian Alps. It represents one of the most active cases in the alpine region, with a sliding surface located at a depth of 70 to 90 m, for a total estimated volume of 30 Mm3. Based on the available in situ monitoring data (meteorological data, piezometric levels, Ground-Based Interferometric Radar displacement vectors), velocity–time curves correlate with the piezometric level trend and rainfall, suggesting a key role of water pressure as an accelerating factor.

Methods: The input data required by the model are pore pressure, reference stresses and initial temperature at the sliding surface, as well as velocity of the landslide body assumed to be a rigid block. In addition, to define the constitutive model of the shear band (modelled as a visco-plastic medium with thermal softening and velocity hardening), thermal and load rate sensitivity of the material are necessary. A preliminary 3D FEM numerical analysis was carried out and the stress distribution at the sliding surface was simulated (step 1). Then, triaxial compression tests with thermal control were performed on rock samples representative of the shear band, defining its mechanical behavior (step 2). To calibrate the model, pore pressure data from in-situ piezometers relative to the period 2014-2018 were introduced and a best fitting between modelled and monitored landslide velocities was obtained (step 3). Finally, velocities were forecasted for the period 2018-2020 and a process of validation was applied using field displacement histories (step 4). Once the model was validated, bias-corrected Regional Climate Model outputs were evaluated and statistically downscaled using a two-step approach (change factors and weather simulators) in order to obtain the projected data (step 5).

Results: The downscaled precipitation allowed to evaluate the piezometric levels up to the year 2100 considering scenarios at warming increment above preindustrial temperatures of 1.5, 2, 3, 4°C, and to analyze the evolutionary response of the landslide. Likewise, the future temperature evolution along the slope and at the depth of the sliding surface was also evaluated and introduced into the model verifying its influence on the landslide behavior.

Conclusions: The model represents a first attempt in the formulation of a predictive tool of landslide evolution, aimed toward the definition of a novel physics-based early warning strategy that can account for future climate scenarios.

COSMOGENIC NUCLIDE DATING OF THE BACK SCARP OF THE ACTIVE REINBENKAN / KRUVNNUT ROCKSLIDE, NORTHERNMOST NORWAY, INDICATES ACCELERATED MOVEMENT IN THE HOLOCENE CLIMATIC OPTIMUM FOLLOWED BY DECELERATION

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Unstable rock slopes pose a threat in the Norwegian fjord lands as catastrophic failures of such slopes historically have resulted in displacement waves causing life losses and destruction in nearby villages. The related hazard of unstable rock slopes is evaluated with systematic mapping to classify the rock slopes (Hermanns et al., 2013). For this classification we use various geomorphological, structural, and rock slope activity observations, including acceleration. The last is difficult to assess as monitoring data exist for only short time periods. Surface exposure dating of slide surfaces with terrestrial cosmogenic nuclides (TCN) have proved to be a useful tool for it.

The west-facing Reinbenkan/ Kruvnnut unstable rock slope has developed as a rock block slide with limited internal deformation along a 350-m-high coastal cliff. Solifluction lobes in surface deposits in close vicinity to the slide attest to prominent freeze-thaw cycles (mean annual temperature is ~0°C today). This rockslide preserves the summit plateau surface nearly intact but has offset it 80 m downslope with a 62°dip and a 7-10° backward tilt. Both flanks of the rotated block are broken, and the toe of the rockslide lies below the coastline, but it cannot be precisely determined on the bathymetric data. Thus, the estimate of displaced volume ranges from 45 to 78 million m3. The back scarp has developed along the crenulated foliation. Limited rock fall deposits on the sliding block indicate stability of the scarp and suitability for TCN dating.

We sampled the 80-m-high back scarp with 10 samples over a length of 70 m for cosmogenic 10Be produced in quartz to determine the exposure history, calculate paleo-slip rates, and determine any acceleration. Modern deformation rates were determined using dGNSS, satellite-based InSAR of natural surfaces and reflectors.

The TCN ages decrease in the slide direction from 10.9 ± 1.5 to 0.7 ± 0.1 kyr. The paleo-slip rates calculated by dividing age by slip length below the top of the back scarp indicate a slow start of sliding (2 mm/yr), and an acceleration to 15.4 mm/yr between 8 and 5 kyr. Near the foot of the backscarp the paleo-slip rate is 11 mm/yr. This is the same velocity as measured today with dGNSS and satellite based InSAR. The InSAR data from corner reflectors indicate that rock slope deformation today only occurs between June and September.

During the Holocene climate optimum (HCO) (8-5 kyr ago) mean annual temperatures were 1-2° warmer and winter temperatures up to 4° warmer in northern Norway (Lilleøren et al., 2012). We interpret that higher temperature during the HCO resulted in longer deformation periods and thus higher average slip rates. Rock slope deformation today has thus not yet accelerated to the 8-5 kyr rate, however continued climate warming may enable such acceleration.

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ROCK SLOPE INSTABILITY ALONG THE COASTLINES OF SVALBARD: THE EFFECTS OF LITHO-STRUCTURE AND PERMAFROST DEGRADATION

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Purpose: Permafrost degradation and changing precipitation patterns due to climate warming are increasingly recognized as major contributors to rock slope failures in arctic and high-mountain environments. The project aims to understand the stability of coastal cliffs along coastlines of Spitsbergen to identify the driving factors of active rock slope deformations and to support hazard assessment.

Methods: Based on detailed geomorphological and structural field mapping, UAV and bathymetric surveys, and GPS measurements, two unstable cliff coast sections are investigated. The two areas have been shaped by postglacial rockslide activity but differ in litho-structural setting, deformation history, and slope exposition.

Results: The west-facing slopes of Forkastningsfjellet at the eastern margin of Isfjorden are the result of a large ~100 million m³ postglacial rock slide that split the rock mass into multiple fault blocks and depressions, creating the pronounced local relief. In August 2016, one of these coastal fault blocks was affected by a rock slide comprising a volume of 175.000 m³. This event was the first major landslide event since at least 1936 and thus suggests the change of landslide activity from a dormant to an active state. The rock slide used an old inherited sliding plane of the postglacial rock slide as the rear rupture surface, attesting a reactivation of pre-existing zones of weakness. Back-calculations show that permafrost degradation and the associated increase in water availability were contributing factors to the rock slope instability and subsequent failure. Increasing occurrence of active layer detachments (ALD) and thermokarst structures on the postglacial rock slide body also evidence a rise in water availability. GPS measurements and UAV-based DEM comparison indicate accelerated movements of the neighbouring coastal block along the same reactivated fault. Gullying of infiltrating surface water along the weak fault zone suggests that a renewed break-off of this cliff segment is imminent. The east-facing slope of Garmaksla at the western margin of Billefjorden is also affected by a huge postglacial rock mass instability, which is explained by a compound rock slide model. The rock slide is delimited to the west by the Balliolbreen Fault, an important pre-existing fault that accommodated multi-phase deformation since Devonian time and served as the main rupture surface. However, the area currently shows no signs of reactivation processes of large slide blocks and lacks typical indications of thawing permafrost like ALD or thermokarst features. Instead, the hillslope is characterised by gravitationally induced rock fall and avalanche-entrained debris deposits, giving rise to talus cones and rock glacier formation.

Conclusions: Both landslide areas comprise kinematically favourable litho-structural conditions, but only the warmer and wetter Forkastningsfjellet shows active measureable rock slope deformation and specific permafrost thaw-related landforms.

PREDICTIVE MODELLING IN LANDSLIDE SUSCEPTIBILITY IN INDIAN HIMALAYAN REGION: SPECIAL FOCUS ON THE ANTHROPOGENIC ACTIVITIES

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Purpose: Geohazard is one of the main devastating hazards in the Himalayan region and this is governed by natural (earthquakes and rainfall) and anthropogenic (road construction, infrastructure development and climate change) activities. Solan district, which falls in Himachal Pradesh in the Himalayan region, is extremely eco-sensitive. This area is very vulnerable to natural calamities and every year, many people lose their lives due to landslides. This research aims to delineate a landslide susceptibility (LS) map using an integrated approach for Solan district, Himachal Pradesh, India. Additionally, examine the role of anthropogenic activities in landslide occurrences.

Methods: Landslide-controlling factors are divided into two groups based on inherent and triggering characteristics. Inherent controlling factors include topographical, lithological/geological, structural discontinuity and hydrological factors and triggering factors include distance to road, normalized difference vegetation index (NDVI), land use & the land cover (LULC) and rainfall. Landslide inventory, consisting of point and polygon data, is classified into two groups: Rainfall-induced landslide (RIL) and Human-Induced Landslide (HIL), to examine the influence of anthropogenic activities on landslide occurrences. To analyse landslide susceptibility, integration of a qualitative (Analytical Hierarchy Process) and quantitative (Frequency Ratio) methods are used to compute landslide controlling factor weights and landslide controlling factor class weights, respectively. Finally, all spatially distributed maps of the landslide controlling factor are combined by a Weighted Linear Combination (WLC) technique in a Geographical Information System (GIS) to produce LS map. The efficiency and performance capabilities of the LS map are assessed by landslide training (80%) and testing (20%) datasets, respectively.

Results: The delineated LS map in the study area is characterized as 'Very Low (19.73%)', 'Low (32.91%)', 'Medium (26.52%)', 'High (14.70%)', and 'Very High (6.14%)', respectively. The very high susceptible class alone contains 40.00% area of the total landslide events and the very low class contains only 0.71% area of the total landslide events. The LS map is acceptable and appropriate as higher percentages of landslide occurrence in the very high susceptible class and a decreasing trend have been observed toward lower susceptibility class. The validation results confirm that the proposed LS map has reasonably good predictive capacity. The success rate and prediction rate curves indicate that the AUC for the training and testing dataset is 82% and 80%. Anthropogenic activities have a positive correlation with the human-induced landslide.

Conclusions: This study improves our knowledge about the impact of human activities and different driving factors for human-induced landslides. This indicates a significant impact of anthropogenic parameters on landslide susceptibility in Solan district. The present study will assist in comprehending the relation of landslide with the anthropogenic factors and recommend inclusion of LULC in susceptibility analysis. The outcomes of the present research will be helpful towards landslide risk reduction.

SESSION 4.11

ASSESSING GEOHAZARDS OF SUBMARINE LANDSLIDES: WHERE ARE WE? AND WHAT ARE WE MISSING?

SUBMARINE LANDSLIDE MAPPING IN THE ITALIAN SEAS. OUTCOME FROM THE MAGIC PROJECT

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The mapping of marine geohazard features, primarily those related to submarine instability, is the first unavoidable step for the correct management of the submerged territory and for the development of the Blue Economy.

A best practice initiative, which has seen an entire national marine geology scientific community come together to achieve this goal, is the Italian national project MaGIC (Marine Geohazards along the Italian Coasts), funded by the Civil Protection Department with 5.25 million €.

The project was based on the acquisition and interpretation of high resolution multibeam bathymetry on the outer platform and upper slope environment. The interpretation was entrusted to research groups that historically studied the areas for which they were responsible, so as to transfer knowledge deriving from other types of data not directly collected in the project (such as seismic, sampling, etc.) into the geomorphological interpretation.

The main outcome of the project was the definition of standard criteria for interpretation and cartographic representation with the production of maps of geomorphic features related to marine geohazard for most of the Italian continental margins at a scale of 1:50,000.

The entire community of Italian researchers in Marine Geology (7 universities, 3 CNR institutes, the OGS institute from Trieste) participated in the project. A sheet of the map was also produced in French waters by the GeoAzur Research Institute.

More than 40,000 nautical miles of multibeam data were acquired and 73 maps (A0 format, 1:50,000 scale) were produced.

The detailed cartography using high-resolution multibeam imaging allows, even in the absence of a complete knowledge of the instability mechanisms and direct dating, to have reliable geohazard indicators, on the basis of which to carry out susceptibility assessments and to design hazard and multihazard scenarios.

One of the main results was to highlight how widespread the instability processes are along the Italian continental margins and how high the geohazard for human settlements and infrastructures is in offshore and coastal areas.

A particularly sore point is the difficulty of transmitting this information to the territorial authorities and to decision makers in general. To this end, a paper atlas was produced, distributed in over 1,000 copies to all coastal municipalities, coastguards, marine protected areas and other technical authorities with competence on the coast and offshore areas.

A LARGE-SCALE LANDSLIDE AFFECTING THE SOUTHWESTERN MEDITERRANEAN SEA

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Purpose: The southwestern Mediterranean has undergone a Neogene geodynamic evolution related to the convergence between Eurasian and African (Nubian) plates. The growth of an oceanic crust bordered by alpine cordilleras has configured the Algerian basin partially surrounded by still deforming continental margins. The Messinian salinity crisis produced the deposition of evaporitic layers mostly in the abyssal plain with a scarce and local presence in the continental margin. The progression of the convergence has determined the instability of the former passive margin. In this context, this works analysed a large-scale landslide.

Methods: Dataset used in this study comprises swath bathymetry, magnetic anomalies and multichannel seismic records with different degrees of resolution.

Results: The large-scale landslide is characterized by an extensional updip domain formed by a > 300 km long, arcuate and composite headscarp. It bounds downslope individual rotational scars of varying lengths in plan view that are rooted down to MSC layer. This domain defines a fringe of variable width, from a few to > 35 km, that roughly parallels the distal Palomares-Cartagena margin and the transition between the Alboran basin and the Algerian abyssal plain. The downdip compressional domain is wider than the extensional one and extends unevenly along the abyssal plain. It is defined by the lateral motion of the entire sequence of sediments overlying the MSC salt deposits and is characterized by contraction (folding) and salt diapirism. Salt arises to different stratigraphic levels forming diapir- and pipe-like features whose faults making up their crests extend upwards and locally reach the seafloor. These features are most abundant in the northern area of the Palomares-Cartagena margin.

Conclusions: This basin-scale landslide is interpreted as a gravity-driven deformation that results from the interplay between tectonics that accommodates the Eurasian and African interaction, the MSC salt layer distribution, and the subsidence of the abyssal plain. The MSC salt layer works as the detachment level above which the entire overlying sediment sequence slides and moves towards the deepest areas of the subsiding abyssal plain. The uneven development of the extensional and contractional domains of this landslide is mainly controlled by the regional slope gradients that are onshore and offshore structurally controlled. In the Palomares-Cartagena margin, the tectonic plate interaction forms the onshore Aguilas Arc that provokes the tilting of the entire continental margin, being most important in the northern sector. Westwards, in the transition between the continental Alboran basin and the oceanic Algerian basin, the convergence favors an overstepping transition domain toward the abyssal plain. In summary, the southwestern Mediterranean is being shortened and sediment deformation is concentrated around the contact between continental margins and the oceanic crust favoring a gravity-driven deformation at basin scale.

SUBMARINE LANDSLIDES IN HIGH LATITUDE CONTINENTAL MARGINS: THE TSUNAMIGENIC STORFJORDEN SL-1 LANDSLIDE

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Purpose: High latitude continental margins undergone the effects of global climatic change and ocean warming, that are key factors that may induce future landslides. This is because the increase of water temperature may contribute to gas hydrates breakdown which leads to increase pore pressure of sediments. Other important factor is the seismicity related to glacio-isostatic adjustments; the isostatic uplift decreases the confining pressure and induce fault activity and hence seismicity. Therefore, a modelling approach to understand the tsunamigenic potentiality of submarine landslides will provide new perspectives on tsunami hazard threat in these regions.

Methods: Here, we use the Landslide L-ML-HySEA numerical model to analyze the tsunamigenic potential of the Storfjorden SL-1 landslide (Southwestern Svalbard), and thus evaluate the hazards of similar structures that may develop in the future.

Results: This landslide extends from the shelf-edge at 420-480 m down to > 1900 m water depth, is ~ 60 km in length and covers an area > 1300 km2. Modelling results show that the tsunami waves present low amplitude values in open sea, reaching several meters at the coastal area where arrival times start at 50 min. Tsunami waves comprise two initial wave dipoles, with troughs to the northeast (Spitsbergen and towards the continent) and humps to the south (seawards) and southwest (Bear Island), reaching more than 3 m of amplitude above the landslide, and finally merging into a single wave dipole. The formation of dipoles is related to the evacuation area at the slide scar by the instantaneous landslide displacement, and by the uneven landslide deformation having different velocities during its runout. In fact, a new wave dipole is formed, opposite to the initial ones, when the faster moving body reaches the slower one, and both merge increasing the thickness of the Storfjorden SL-1 landslide. The local bathymetry of the continental shelf, characterized by glacial troughs and a shallow bank, controls the direction of tsunami wave propagation with a crescent-shape front in plan view, and is responsible for shoaling effects of amplitude values (-4.2 to 4.3 m), amplification (-3.7 to 4 m), diffraction of the tsunami waves, as well as influencing their coastal impact times.

Conclusions: These results underline the need to increase the research and the knowledge of seafloor morphological features and slope instability in these remote areas. The modelling of ancient landslides and the interaction of several landslides that could be triggered simultaneously by seismicity with tsunamigenic potential, are necessary to evaluate and mitigate the hazard of polar regions.

TSUNAMI HAZARD ASSESSMENT OF COMPLEX MASS WASTING PROCESSES THROUGH NUMERICAL MODELING: THE CASE OF ASSI LANDSLIDES (IONIAN CALABRIAN MARGIN, SOUTH ITALY)

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Purpose: Mass movements along submarine margins are among the most hazardous tsunamigenic processes, due to their frequent occurrence, the steep slopes, and their closeness to coastal urban or industrial settlements. The Mediterranean Sea is characterized by active geology, including densely populated coastal areas, enhancing considerably the exposure to such phenomena. The identification of submarine landslides and the characterization of major mass transport dynamics and processes occurring along continental margins is then crucial. In this work, the reconstruction of the sequence of events (named Assi landslides) occurring along the Ionian Calabrian Margin (ICM) is described by means of geological and geophysical evidence, and the related tsunamigenic hazard quantified through numerical techniques. A set of three scenarios has been realized, representing slide motions characterized by different features: the aim is to evaluate the influence of such variation on the tsunami generation and impact on the coast.

Methods: High-resolution bathymetric and sub-bottom data contributed to identify and reconstruct the dynamic of three related sliding events: the Assi failures. The simulations follow a well-defined numerical routine, dealing in sequence with the different phases of the whole tsunami process: sliding dynamics, tsunami generation, wave propagation and impact on the coast. Recent examples of its application are visible in Zaniboni et al. (2021), Gasperini et al., (2022), Gallotti et al. (2023) and references therein.

Results: The ICM Is characterized by a very complex mass transport history, evidenced by several scars along the slope and related deposits at its toe indicating multiple landslide events. In particular, the three analyzed Assi landslides lie on a forearc basin that generated during the SE migration of the Calabrian arc since the Middle Miocene and experienced a rapid uplift since 1Ma that steepened the slope (Ceramicola et al. 2014). Using geological and geophysical data, three failure events occurring since Pleistocene were reconstructed in terms of dimensions and volumes, and used to assess the possible tsunami such events may have generated. The numerical simulations show that the reconstructed mass motions can generate waves hitting the coast with height exceeding 2 m: though not catastrophic, these can provoke damages on facilities and boats and drag people into the water. The resultant tsunamis have specific features, depending on the source characteristics (dimension and geometry, depth of detachment, sliding dynamics). To assess the dependance of the tsunami attributes on the source properties, a sensitivity analysis has been performed by changing the thickness of the three original scenarios. In this way, some interesting correlations are found between quantities describing the landslide source and other accounting for the ensuing tsunami.

Conclusions: The complex mass wasting processes along the ICM have been studied and reconstructed by means of geophysical and geological investigations. Among the diverse events, three scenarios have been selected as representative of source features (volume, depth, dynamics) and the respectively generated tsunami effects have been evaluated through numerical modelling. The sensitivity analysis provides intriguing landslide-tsunami correlations, that can be extended to other similar submarine morphologies and to the study of the related tsunami hazard.

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SUBMARINE LATERAL SPREADING IN THE AGUILAS HIGH MASS FLOW DEPOSITS (PALOMARES MARGIN, SW MEDITERRANEAN)

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Purpose: The Aguilas High (886 to 1400 meters water depth) located in the Palomares margin (Spanish margin of the SW Mediterranean), is affected by numerous mass flow processes of different sizes. As a result of the Eurasian–Africa plate collision the seismicity in the area is characterized by moderate to low magnitude earthquakes with recurrent events of Mw >4 for a return period of 1.6 years, and a deduced PGA (Peak Ground Acceleration) of >0.17 g for a return period of 500 years in the offshore area (Nespereira et al., 2019). Instability processes affecting the High is hypothesised to be related to creep processes that are initially driven by the liquefaction of clayey sediments. Cohesive sediments under the shake of seismic events may develop liquefaction or cyclic softening causing lateral spreading movements (Idriss and Boulanger, 1966).

Methods: This work is based on bathymetric, geologic and geotechnical data obtained on board the R/V Sarmiento de Gamboa. Different multibeam echosounder datasets, including the high-resolution data recorded by an AUV in selected areas, were merged. Three gravity cores (GC-3, GC-4 and GC-5) analysed with a Geotek Multisensor Core Logger (MSCL) and different geotechnical tests (AENOR, 1999) allowed to characterise both sedimentary and geotechnical properties of the studied area. Also, five CPTu tests (Figure 1) carried out by a Neptune 5000 penetrometer have been used for evaluate empirically the soil liquefaction potential (Seed and Idriss, 1970).

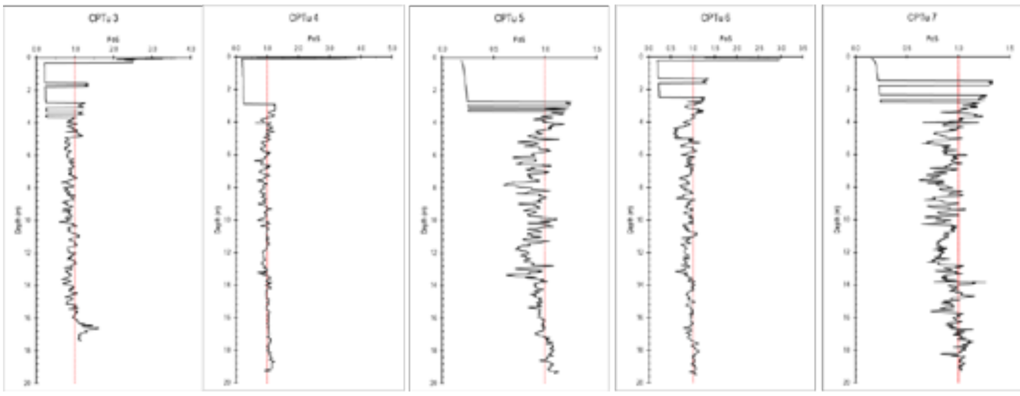

Fig. 1: CPTu tests used in this work for soil liquefaction assessment.

Results: Geomorphological features (e.g. scars) and geotechnical characteristics obtained are compatible with creep and lateral spreading processes in the study area. Sediments are defined as fine soils with high plasticity with soft to very soft consistency and classified mainly as MH according to the USCS. It is remarkable the existence of a change in the Su gradient at ≈10 m below seafloor, where a potential sliding surface would be located. CPTu test identified mainly fine soils, SBT 3 (clays to silty clays) and SBT 4 (silt mixtures) and the FoS for liquefaction is lower than 1.

Conclusions: The Aguilas High is affected by progressive and recurrent mass flows (e.g. lateral spread) triggered by seismic induced liquefaction.

VOLCANIC ASH CAN ACCOMMODATE FRICTIONLESS SLIDING IN SUBAQUEOUS ENVIRONMENTS

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The presence of so-called weak layers is increasingly recognised as an important agent for the occurrence of large submarine landslides on low angle slopes. Whether volcanic ash layers are favourable or adverse for slope stability is highly debated. Here, we show evidence from pore water anomalies and sediment cores for very recent lateral movement of a 2 m thick undisturbed sediment package overlying a 0.2 m thick ash and lapilli layer. The sediment movement occurred within an almost flat (slope gradient <0.5°) sediment minibasin at the continental margin of Eastern Sicily, Italy, most likely in 2021. The ash and lapilli layer must have acted as an almost frictionless surface that allowed translation of the sediment package without any disturbance, erosion or shearing at its base. This is the first field evidence for almost frictionless sliding, which, prior to this study, has been proposed based on conceptual models and laboratory tests only.

3D MORPHOLOGY OF BASAL SHEAR SURFACES: FINGERPRINTING LONG-RUNOUT SUBMARINE LANDSLIDES

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Purpose: Submarine landslides are ubiquitous features of continental margins and play a major role in the shaping of offshore basins and ocean floors. Their occurrence poses threat to seabed infrastructures and coastal human population; the latter largely due to the tsunamigenic characteristic of submarine failures. Investigation of seabed using high-resolution multibeam bathymetric data is currently the key method for identifying and mapping the occurrence of morphologies indicative of landslides (i.e. crowns, furrows, scours, blocks etc). This is the first step for assessing the potential hazard a specific portion of seabed is exposed to. However, highly mobile submarine landslides typically are known to attest run outs of several tens of kilometers and display fully evacuated head scarps that expose the basal shear surface above which the landslide mass has moved down dip (Figure 1). Occurrence of this type of mobile landslides might be missed in circumstances where seabed investigation is restricted to areas where landslide masses have transited leaving exposed their basal shear, and their deposits are not there present.

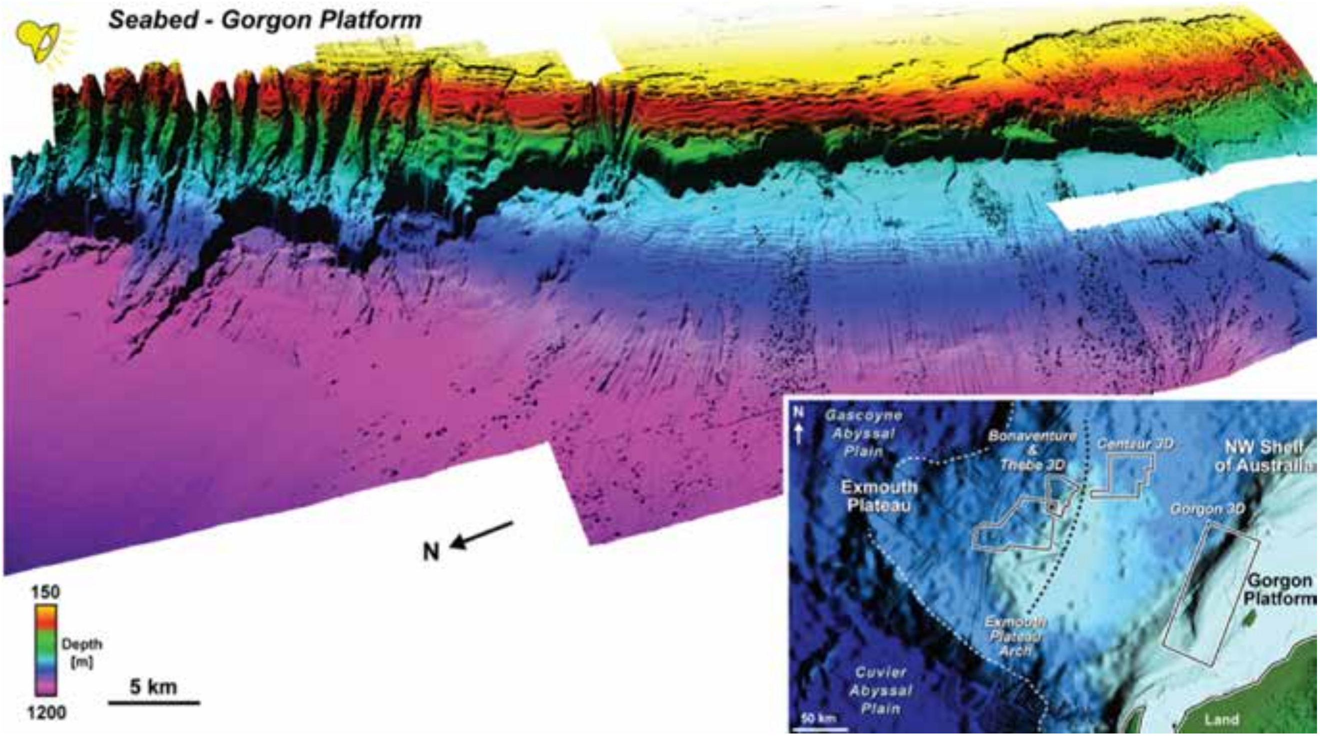

Fig. 1: 3D seabed rendering of the Gorgon Platform in the southern segment of the NW Shelf of Australia. The image shows that a stretch of the Gorgon Platform ~ 70 km wide has been affected by a large failure that left a series of coalesced head scarps up to 250 m high along the rim of the platform. Note the linear erosional features left by the transit of the landslide mass now located several tens of kilometers down-dip of the head scarp.

Methods: We present detailed seismic geomorphological results from the mapping of a number of basal shear surfaces from several recent submarine landslides from the North West Shelf of Australia. Mapping was achieved through detailed interpretation of recently acquired, high-quality, 3D seismic reflection datasets. Seismic attributes were also implemented to aid interpretation and visualization of morphological characteristics of landslides.

Results: The analysis shows peculiar morphological characteristics typifying basal shear surfaces of recent submarine landslides in the study area. Amongst a variety of features, narrow (metric to decametric) erosional features are commonly observed extending along the direction of main transport of landslides. These features are arranged in sets that show great variability with linear and parallel (or sub-parallel) erosions as well as diverging from the source areas, to cross-cutting sets also observed. These features affect areas hundreds of square kilometers wide, likely providing indications for the extent of the failures that have produced them and their kinematic evolution (Figure 1).

Conclusions: This contribution highlights the importance of defining a geomorphological framework for the morphologies observed along basal shear surfaces, as these have the potential to provide key insights on the kinematics of failure, provenance and size of long-runout submarine landslides, especially when the extent of seabed investigation is limited. Such framework might hold value for erecting seabed maps depicting potential hazards associated with landslide emplacement.

SESSION 3.1

RECENT ADVANCEMENT IN LABORATORY AND IN-SITU TESTING METHODS FOR LANDSLIDE AND SLOPE ANALYSES (part II)

IMPACT OF TEMPERATURE, OVERBURDEN PRESSURE AND PLASTICITY CHARACTERISTICS ON THE REDUCTION IN SHEAR STRENGTH OF THAWING FINE-GRAINED SOILS

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Thawing or even warming of the permafrost resulting from climate change is expected to cause slope failures and cause subsidence-induced disturbances to building foundations, pipelines and other infrastructure. These issues have the ability to produce cascades of disastrous events. For example, a slope instability in the New Zealand permafrost resulted in rapid rock-ice flows, earthquakes and floods. The instability was triggered by an increase in the temperature of the permafrost, which resulted in an increase in the unfrozen water content and a weakening of the underlying materials. To better understand the relationship between temperature, overburden pressure and plasticity characteristics on the reductions in shear strength of the underlying fine-grained soils in permafrost regions, a temperature-controlled direct shear device was developed. Laboratory prepared mixtures of kaolinite and quartz were frozen to -10°C and thawed to temperatures between -10°C to +4°C following which their shear strength was measured. The results showed that an increase in temperature would result in a rapid reduction in shear strength until the melting point of ice is reached. After this point, which depended on the overburden pressure, further increases in temperature resulted in slight increases in the shear strength of the material. This increase is hypothesized to be a result of the densification of the soil mass as water drains from the sample. The decrease in shear strength was found to be more pronounced in samples with higher plasticity indices.

MONITORING OF SOIL STRAIN PROFILE CAUSED BY FREEZE-THAW CYCLE USING FIBER OPTIC SENSER

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Purpose: In the global cryosphere, pronounced deformation of slopes due to freeze-thaw actions have been widely reported. To further evaluate and predict the possible landslides in cold regions, the strain profile of the whole slope is necessary to be monitored and investigated during freeze-thaw cycle. Compared with conventional strain sensors, fiber optic sensing technology is proven to be highly sensitive, small, waterproof, and immune to electromagnetic interference. In addition, it can be processed for the measurement of long-term periods and short spatial resolution. Therefore, it is suitable to be used for monitoring slope deformation and early detection of slope failure surfaces. To apply this new approach for slope health monitoring in cold regions, the priority is to assess its performance at a sub-zero temperature in the soil. The effects of pore water transferring to ice on interface between soil particles and optic fibers is still not clear. The feasibility of the monitoring by using optic fiber on ice lenses formation due to water migration is also unknown.

Methods: In this presentation, a small-scale soil column test is conducted by using silty clay to investigate the evolution of strain and temperature profile during the one-sided freeze-thaw condition. By adopting distributed fiber optic sensing (DFOS) combined with optical frequency domain reflectometry (OFDR), the strain and temperature distribution along the vertical direction in soil column can be monitored with the spacing interval of 2.6 mm and the time interval of 1 s. Three optical fibers are buried in a soil column (two for strain measurement and one with a plastic tube cover for temperature measurement). The general set-up of the experiment is shown in Figure 1.

Results: Experimental results reveal that with the penetration of frozen fringe during freezing, clear heave and contraction develop at frozen and unfrozen zones respectively. The accumulation of ice lenses in vertical direction segregates the soil particles in frozen zone. Water migration from unfrozen to frozen zone due to temperature gradient results in a contraction of unfrozen soil during freezing. The soil settlement along the vertical direction is observed mainly at the surface layer during thawing.

Conclusions: This study has presented a new framework to monitor the strain profile in frozen soil using fiber optic sensing technology. Preliminary results of strain profile during freeze-thaw are collected and analyzed to enhance the understanding of soil response in cold regions. For further investigation, DFOS-OFDR is recommended to apply for the monitoring of ice layer formation and prediction of the possible failure surface for man-made slopes in cold regions.

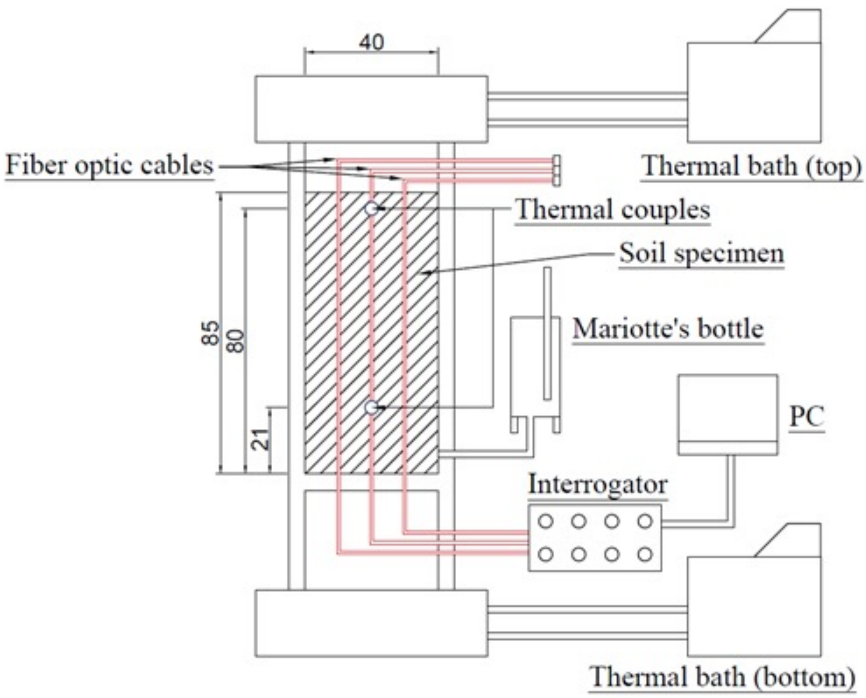

Fig. 1: Schematic of the experimental set-up.

EXPERIMENTAL INVESTIGATION ON RATE EFFECTS OF SHEAR-ZONE SOIL INFLUENCING KINEMATICS OF BEDDING LANDSLIDES

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Purpose: Bedding landslides are normally developed in sedimentary layers and are characterized by basal shear zones. Influenced by external forcings like intensive rainfall, seismic wave, and human activities, they may suddenly accelerate or even collapse without any premonition, posing serve threat to local residents and infrastructures. Numerous in-situ observations have indicated that the kinematics of bedding landslides are largely related to the mechanical behaviour of their shear zones, of which soil exhibit high content of clay-rich materials. Previous studies usually invoke hydrological or seismic theory to explain the weakening of shear zone, while only a few works focus on the residual-state strength of shear-zone soil affected by velocity variation during landslide movements. Therefore, the residual-state rate effects of shear-zone soil should be comprehensively investigated through experimental approaches for a better understanding of the kinematic mechanism of bedding landslides.

Methods: The test materials are collected from the exposed shear zone of a real bedding landslide, which is a famous catastrophic failure in the Three Gorges Reservoir area in China. Ring shear apparatus is employed to investigate the mechanical behaviour of shear-zone soil at the residual state. Both soil test and interface test are implemented to study the rate effect of shear-zone soil and interface with different approaches. The soil is first brought to the residual state with large shear displacement at a drained condition of 0.02 mm/min. Then the displacement rate is increased by step to investigate the variation of shear resistance mobilized by the test sample with increasing velocity. Before each shearing step, a preconsolidation procedure is carried out to mimic the overconsolidation state of the basal shear zone in bedding landslides.

Results: The shear-zone soil exhibits different rate-effect behaviours in the soil tests and the interface tests. For the pure soil samples, the rate effect shows a non-monotonic tendency characterized by rate-weakening behaviour during slow shearing and rate-strengthening behaviour during fast shearing. Affected by the soil-rock interface, the rate-effect behaviours of the soil largely depend on the surface asperity and stress level.

Conclusions: The rate-effect behaviour of shear-zone soil plays a critical role in dominating the mobilization of the basal shear zone in bedding landslides. The interface between shear-zone soil and bedrock greatly influences the rate effect of the shear-zone soil, making its rate-weakening tendency become more prominent at high velocities. Therefore, the polished bedrock may facilitate the viscous flow of the shear-zone soil, leading to sudden acceleration of the whole sliding mass.

SOIL IMPROVEMENT THROUGH MICROBIAL-INDUCED CEMENTATION

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Purpose: Biological treatment is an emerging technique in treating soil and other geomaterials for altering their mechanical and hydromechanical properties. In this presentation, following a brief review of the Microbial-Induced Calcite Precipitation (MICP) process, its application to a sand, mine tailings and an organic soil are demonstrated based on laboratory research carried out at Western University since 2015.

Methodology: The effect of MICP is primary assessed through laboratory direct simple shear tests on cylindrical specimens of 70 mm in diameter and about 20 mm high. Specimens are reconstituted used various methods including moist tamping, pluviation through air and slurry deposition. Biologically-treated samples are initially mixed with a microbial solution of urease-producing bacteria, urea, yeast extract, and ammonium chloride. After several days of biological treatment, the specimens are flushed with a cementation solution of calcium chloride and urea as a source of calcium for bacteria to precipitate calcite. The treated tailings are subsequently sheared under undrained (constant-volume) or drained conditions. In addition, to direct simple shear tests, some specimens were also sheared in direct shear box tests or compressed in a oedometer cell to determine their compressibility. Scanning electron microscopic images and X-ray diffraction analysis are also carried out to visualize the MICP cementation or characterize the precipitates. The amount of calcite precipitated in each specimen is also measured by dissolving specimens in a solution of 1M HCl. In addition to treated specimens, series of direct simple shear tests were also conducted on original untreated specimens for comparison with the treated specimens.

Results: The results demonstrate significant improvements of shear strength, liquefaction resistance and stiffness of various geomaterials. For sand specimens, including Fraser River sand and mine tailings, liquefaction potential was significantly reduced, and the risk of liquefaction was effectively eliminated as their undrained shearing behavior transformed from a contractive to dilative behaviors. This implies the high resistance of treated specimens and that MICP treatment could be an efficient technique to minimize the risk of landslides triggered by both static and seismic events. In addition to shearing resistance, the compressibility of peat specimens was significantly reduced following the biological treatment. This further suggest that MICP treatment could be used to stabilize organic deposits, reduce their compressibility under loading, and allow direct construction on such deposits without the need for their removal or deep foundations.

Conclusions: Ongoing research at Western University demonstrate the significant rises of monotonic strength, cyclic resistance, and stiffness of a wide range of geomaterials treated by MICP. These are supported by particle-level changes in these materials measured through Scanning Electron Microscopic Images and X-ray diffraction analyses. These observations support the use of MICP as an innovative technique to stabilize slopes and minimize the risk of landslides.

DYNAMIC RESPONSE AND FAILURE MECHANISM ANALYSIS OF A CROSS-FAULT SLOPE BASED ON LARGE-SCALE SHAKING TABLE TEST

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Purpose: The 2008 Wenchuan earthquake indicated that landslide damage and spatial distribution exhibit an upper-footwall effect. However, how the fault dislocation will affect the slope dynamic response during the earthquake and the failure mechanism of the slope with a reverse fault aren't clearly studied.

Methods: To address this, the dynamic response and failure mechanism of a slope with fault dislocation is investigated based on the experiment of shaking table test in this study. Firstly, a rigid model box being able to simulate the reverse fault movement was designed. A shaking table was used to test a horizontally stratified slope across a fault with a 50° dip angle. The slope was subjected to sinusoidal and Wenchuan wave excitation with different amplitudes and frequencies, and acceleration sensors and strain gauges were installed to measure the slope's dynamic response. A high-speed camera was used to record and analyze the slope failure process with fault dislocation based on the particle image velocity measurement method. Then, the dynamic response law, footwall effect, and mechanical process of fault movement across a fault slope during an earthquake were investigated in the experiment.

Results: The test results show that although the acceleration response of the hanging wall and footwall show elevation effect and surface effect in both vertical and horizontal directions, the amplification factor of the hanging wall is larger than that of the footwall. The analysis of dynamic response and failure characteristics of slope in staggered motion shows that the acceleration response after staggered motion is slightly larger than that before staggered motion, and the acceleration response before staggered motion is the least. The main fracture generation process of the hanging wall is a tensile failure, and the footwall is a tensile failure followed by shear failure. The main failure mode of the cross-fault slope is the formation of tensile cracks at the top of the hanging wall, which connect and extend to the footwall to form a sliding surface.

Conclusions: The test results show that the reflection and refraction of fault on seismic waves significantly increase the amplification effect of slope acceleration. The amplification factor of the hanging wall is larger than that of the footwall. The main fracture generation process of the hanging wall and the footwall are different in staggered motion This study provides valuable insights into the mechanical behavior of fault movement across a fault slope during an earthquake. The findings could be used to improve our understanding of landslide damage and spatial distribution during future earthquakes, helping to mitigate potential disasters.

Keywords: cross-fault slope, dynamic response, upper-footwall effect, failure mechanism, shaking table test

THEPHRA LAYERED SHALLOW LANDSLIDES AND RELATED GEOTECHNICAL PROPERTIES OF TEPHRA MATERIALS CONSIDERING THE ISOPACH MAPS

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Purpose: In recent years, tephra layered shallow landslides due to earthquakes and heavy rainfalls have repeatedly occurred in specific tephra layers (volcanic ash layers) in volcanic regions in Japan. The Izu Oshima landslide disaster caused by heavy rainfall in 2013, the Kumamoto earthquake in 2016, and the Hokkaido Eastern Iburi earthquake in 2018 have occurred in Japan. Especially in the Aso region of Kumamoto Prefecture, not only earthquakes-induced landslide disasters but also heavy rainfall-induced landslide disasters in 1990, 2001, and 2012 have repeatedly occurred. On the other hand, an isopach map displays contour lines of equal thickness in a layer over an area which is utilized in stratigraphy, sedimentology, structural geology and volcanology. Isopach maps for Aso volcanoes and Hokkaido Eastern Iburi region are available.

Methods: Tephra layered shallow landslides caused by an earthquake or heavy rain could be characterized by the occurrence of a sliding surface in a specific volcanic ash layer. Focusing on the sliding surface of the tephra layer, we have continuously studied the geotechnical characteristics of these tephra layers. In this study, the sliding surface was observed at the site where tephra layered shallow landslides occurred, and undisturbed and disturbed samples were collected from the tephra layer where the sliding surface occurred. Mechanical properties, physical properties, saturated permeability properties, and content of clay minerals on sliding and surrounding tephra layers were investigated. This study is also focused on the monotonic and cyclic direct shear behaviour for the tephra layers to understand the mechanism of landslide during earthquake. Constant vertical stress and constant volume cyclic direct shear tests were performed to study the cyclic behaviour of the tephra layers.

Results: Results from the study of Hokkaido Eastern Iburi earthquake in 2018 reveal that the physical properties of sliding layers from two landslides demonstrated the same characteristics: non-plastic soil with a low density of soil particles, void ratio, and dry density; these characteristics could influence earthquake-induced landslides. From the constant vertical stress test, strain hardening behaviour was observed. From the constant volume test, shear displacement increased largely during cyclic loading, despite the tephra layer being in an unsaturated state, which were similar to the behaviour of saturated sand during liquefaction. A comparative study was conducted between the layer thickness of the sliding surface estimated from the isopack map and the actual layer thickness measured on in-site.

Conclusions: Characteristics of physical properties and mechanical properties of the sliding layers in shallow landslides of tephra materials on earthquake-induced and heavy rainfall-induced landslides were discussed. An experimental study was carried out on the physical and mechanical properties of the same tephra layer deposited at different locations.

SESSION 2.11

ENHANCEMENTS IN LANDSLIDE DATA ANALYSIS FOR IMPROVED UNDERSTANDING, FORECASTING AND EARLY WARNING SYSTEMS (part II)

DISPLACEMENT TIME SERIES ANALYSIS FOR THE NEAR-REAL TIME DETECTION AND ASSESSMENT OF LANDSLIDE EVENTS

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Purpose: Landslides are one of the most hazardous natural disasters that can cause significant damage to human life and infrastructure, and their timely detection is crucial for reducing the risk of fatalities and property damage. The present work deals with the development of automatic procedures for the identification and assessment of potentially critical events from available monitoring data. In particular, these algorithms could be implemented into the data elaboration process for landslide risk management and early warning purposes.

Methods: The methodology here described relies on the application of two separate algorithms previously developed by the authors, designed for the analysis of displacement time series with a near-real time approach. These models are focused on different aspects of the data elaboration process, and can be applied in synergy for a better understanding of the monitored phenomenon. The first model aims to identify an increasing pattern in displacement rates, by applying a multi-criteria process for the elaboration of monitoring data acquired with automatic instrumentation. This analysis is performed with a “drop-down” process, allowing to define a number of sub-conditions to verify specific features of the dataset. The fundamental hypothesis of the method derives from the creep theory, which defines the presence of a transition from a linear to a non-linear trend in displacement rates. The second one relies on the definition of a threshold value based on the landslide behavior preceding the event of interest. In particular, the reference value derives from the evaluation of equivalent displacements, defined as the displacements previously observed in a time interval equal to the one showed by the potentially critical event. Therefore, they are able to establish a term of comparison to understand if the detected event generated a displacement which does not correspond to a critical occurrence if compared to previously observed events a data trend, despite being geometrically compatible with an accelerating pattern.

Results: The procedure here described was applied to different case studies in order to verify its ability to detect the presence of accelerating trends in the displacement data and assess their relevance in terms of stability conditions by comparing their magnitude with previously available information. To present a more realistic application, real-time data acquisition was simulated. Outcomes of the analyses performed on available displacement datasets underlined the algorithm ability to identify two different stages of the phenomenon evolution over time, correctly identifying the onset-of-acceleration point. Moreover, the application of the threshold assessment procedure to these case studies provided the possibility to define an effective reference value to compare the potentially critical event with previously observed trends.

Conclusions: The methodology here presented successfully achieved the purpose of this study, offering an effective and easily applicable procedure for the detection of potentially critical events and the identification of false alarms in displacement time series. Therefore, it could represent a valuable resource if implemented with other methodologies to increase the reliability and effectiveness of landslide early warning systems.

PINPOINTING IMPENDING CATASTROPHIC FAILURE FROM SPACE: FROM SINGLE TO MULTI-SLOPES AT REGIONAL LEVEL

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Purpose: A promised potential of spaceborne interferometric synthetic aperture radars (InSAR) is a capability for continuous, broad-coverage monitoring of ground deformation with millimeter accuracy, for timely forecasting of impending geohazards such as landslides. The main obstacle in the way of InSAR unleashing this potential is that key precursory ground displacements are, in most cases, a very small subset of the big data from InSAR. Consequently, pinpointing an impending failure becomes very difficult or impossible using traditional methods. This study seeks to develop a framework that can handle such severe imbalances to deliver a prediction of the failure location for real-time decision support.

Methods: Our developed framework deploys a two-phase analysis of the monitoring area which is divided into a grid of small subregions (cells). Phase 1, the characterization phase, applies the concept of outlying aspects mining (OAM) to find the optimal feature subspace (OFS): a subset of features which best distinguishes the landslide source area from the rest. Phase 2, the prediction phase, narrows down the search perimeter and pinpoint the area(s) of highest risk of collapse. The search method: (a) sweeps through a wide range of cell sizes to ensure the OFS is robust to spatial scale variations, and (b) incorporates hypothesis testing to ensure the prediction is not due to random chance. The framework is tested on two Sentinel data sets, each spanning a multiseasonal monitoring period of 2-3 years. The 2014-2017 Xinmo data comprises over 130,000 measurement points (MPs), spread across a 460 km2 area with many slopes. The 2015–2016 Stromboli rockfalls data is for a single slope. In both data, the fraction of MPs in the failure region is disproportionately small (around 0.1% or less) with respect to the total number of MPs.

Results: We found the OFS to be the third quartile of ground displacement for a grid cell. This OFS accurately detects the location of the Xinmo landslide almost 1 year in advance—without false alarms. It also identifies the rockfall areas on Stromboli, a task that is generally infeasible with traditional methods applied to InSAR data. The OFS is simple and efficient to compute, taking only a few seconds on a desktop PC to deliver a prediction.

Conclusions: We shed new light on the use of regional-scale satellite deformation data to advance landslide data analysis for improved understanding, forecasting and early warning. Zooming out of Earth affords a broader search area for signals of impending failure. But the broader the coverage, the bigger the haystack of information, the smaller the needles – the harder it is to pinpoint the target signal. Here we overcome this challenge by developing a framework that combines recent advances from statistical and machine learning and precursory dynamics of granular failure. The framework shows potential for real-time prediction of the location of an impending landslide hazard from big satellite data, thus potentially supporting direct field inspections and/or targeted forecasting of the time of failure.

ANALYSIS OF IOT-BASED FIELD MONITORING DATA FOR LANDSLIDE WARNING AT REGIONAL SCALE: A PILOT STUDY

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Purpose: Predicting the onset of landslides triggered by extreme rainfall events is always very challenging. This study aims to increase the accuracy and the reliability of warning models addressing rainfall-induced shallow landslides and debris flows within operational territorial early warning systems (Te-LEWS), by employing a diffuse network of weather and geo-hydrological IoT sensors and a novel strategy of analysis of these monitoring data.

Methods: The use of in-situ sensors and field data for landslide warning purposes poses many challenges: in operational terms (data acquisition, storage, transmission and analysis), in financial terms (costs related to sensors' purchase, installation and maintenance), as well as for the real-time analysis of the monitoring data (warning model definition, calibration and validation). For these reasons, the deployment of in-situ monitoring data within operational Te-LEWS is most typically limited to rainfall measurements, while the adoption of other types of measurements is only considered within local warning systems. This pioneering pilot study explores and discusses how a large number of IoT geo-hydrological monitoring data can be profitably used to complement rainfall measures for operational purposes within Te-LEWS. The IoT monitoring network is based on the following elements: a relatively large number of low-cost sensors measuring rainfall, groundwater (soil water content, soil water potential, porewater pressure) and surface water (stream flow) conditions; low-power data acquisition; a telemetry setup for data storage and transmission. The analysis of the monitoring data is based on: real-time processing of the data on an online server; fast visualization of ensembles of measurements; correlations among time series of sensors of the same type; correlations across measurements of rainfall, groundwater and surface water data.

Results: The study started recently and is being conducted considering the following sequential phases: 1) choice of technologies and instruments to adopt in the initial IoT monitoring network and for data analysis; 2) acquisition of initial set of instruments and installation in an initial test area; 3) initial assessment of monitoring instruments, telemetry network, and real-time data processing algorithms; 4) review and update of technologies and instruments to adopt in the study; 5) acquisition of other sets of instruments and installation in existing or new test areas; 6) data processing and analysis; 7) development of new warning model for Te-LEWS. If needed, phase 4 to 5 may be repeated. At the conference, results from the initial 5 phases of the study will be presented.

Conclusions: The initial phases of this pilot study, aimed at developing an IoT-based network of sensors supporting the warning model of Te-LEWS for rainfall-induced landslides, indicate that the use of IoT technologies and appropriate data analysis algorithms provides relevant additional information to system managers and stakeholders during emergency phases.

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DEFINITION OF STATISTICAL AND PROBABILISTIC THRESHOLDS FOR RAINFALL-INDUCED LANDSLIDES USING AN UNBALANCED DATASET: A CASE STUDY IN SHAANXI PROVINCE (CHINA)

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Purpose: Rainfall-induced landslides often cause numerous casualties and economic losses worldwide. Implementing a territorial landslide early system (Te-LEWS) is a cost-effective and non-structural approach to mitigate landslide risks at regional scale. The warning model is commonly based on rainfall thresholds, which represent the rainfall conditions that, when reached or exceeded, are likely to trigger landslides. Rainfall thresholds are typically defined based on statistical or probabilistic approaches. However, the definition of thresholds using both approaches for unbalanced landslide datasets is not straightforward. This study proposes a methodology for defining reliable statistical and probabilistic thresholds for such datasets.

Methods: For defining statistical rainfall thresholds: i) an automatic tool is used to reconstruct rainfall events; ii) cumulated rainfall-duration thresholds are defined at several non-exceedance and exceedance probabilities, separately considering rainfall events responsible for landslides (positive thresholds) and rainfall events not responsible for landslides (negative thresholds); iii) the optimal one showing the best performance is determined. For defining probabilistic thresholds: i) another feature extraction tool is employed to derive hundreds of rainfall features automatically from reconstructed rainfall events; ii) a feature importance analysis approach (Monte Carlo filtering) is used to select the features most sensitive in identifying triggering and non-triggering events; iii) one-dimensional and two-dimensional Bayesian approaches are performed to assess landslide probability for each single feature and combination of two features; iv) optimal 1-D and 2-D thresholds and critical probability values are determined.

Results: The methodology was applied in Lueyang county, Shaanxi province (China). A catalogue comprising 176 landslide records from January 2018 to December 2021 (strongly unbalanced, nearly 90% of records occurred on two dates) and corresponding hourly rainfall measurements from 20 rain gauges were used to reconstruct rainfall events and extract rainfall features. Among the defined statistical thresholds, the best-performing one is the threshold defined at 5% exceedance probability by considering non-triggering events, and it is characterized by significantly lower uncertainties than those defined considering triggering events. Both optimal 1-D and 2-D probabilistic thresholds employ 5% as the critical probability value. The best-performing 1-D one adopts extracted absolute energy to represent rainfall conditions, while the 2-D one uses a combination of standard deviation and cumulated rainfall. It is worth noting that the best-performing probabilistic thresholds performed significantly better than those derived by applying common rainfall features (intensity, event rainfall, and duration).

Conclusions: The quantity and distribution of samples greatly affect the reliability of statistical thresholds. Considering negative samples, characterized by adequate sample quantity and distribution, improves the reliability of the derived thresholds. The performance of probabilistic thresholds depends on the sensitivity of rainfall variables used to identify landslides and non-landslides because the Bayesian approach considers both triggering and non-triggering events. Exploring more rainfall features is key to exploiting useful information that may be available in unbalanced datasets.

DEVELOPMENT OF SURFACE DISPLACEMENT DUE TO THE RISE AND LOWERING OF GROUND WATER LEVEL IN A SANDY MODEL SLOPE

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Purpose: Measurement of the displacement on a slope is an effective tool to predict an onset of a shallow landslide. Many researchers proposed the procedures for predicting a failure time of a surface layer of a slope, or the displacement of a slope which is included in an area of a deep-seated landslide based on the measurement of the displacement. The displacement on the slope increases not only with the rise in a ground water level (GWL) due to rainfall infiltration but also under the constant or lowering GWL in the case of a rainfall-induced landslide. It sometimes increases up to failure of the slope under constant or lowering GWL. The mechanism of the former has been already examined and modelled in many literatures while the latter has been examined only in few studies. This paper proposes the model for predicting displacement on a slope under rising and lowering GWL based on the measured displacement on sandy slope model.

Methods: Measurement of surface displacement on a large-scale sandy model slope under repeated artificial rainfall was conducted and the measured data were analyzed to simulate the displacement. Four rainfall events were given to the model slope. Figure 1 shows the relationship between the displacement and GWL throughout the experiment. It is recognized that the displacement developed not only with rising GWL (durations II and IV) but also with constant GWL (duration I) and lowering GWL (duration III). The volumetric water content increased with the rainfall infiltration without the generation of GWL and it might have caused the development of the displacement at duration I. The model for simulating the displacement consisted of the GWL-driven displacement model and creep model. The GWL-driven model was formulated to simulate the displacement due to the rise in the GWL based on the displacement – GWL at duration IV while the creep displacement model simulated the displacement with constant or lowering GWL based on the relationship between the velocity and acceleration of the displacement on the slope. The former was adopted under increasing GWL (durations II and IV) while the latter was for constant or decreasing GWL (duration III).

Results: Figure 2 shows the comparison of the simulated displacement to the measured displacement. The displacement at duration I was out of the target of the simulation because it developed under unsaturated condition. The simulated displacement was a little bit larger than the measured displacement at the first rising GWL (duration II) while the simulated displacement agreed well with the measured displacement at decreasing GWL (duration III). The simulated displacement at duration IV (with increasing GWL) agreed well with the measured displacement without the range of almost constant GWL.

Conclusions: The proposed model could simulate the development of the surface displacement not only with rising GWL but also under lowering GWL, by GWL-driven displacement model and creep displacement model, respectively.

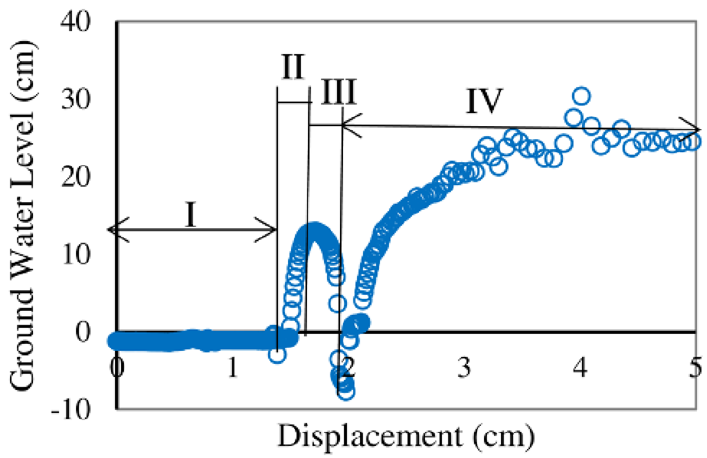

Fig. 1: Measured displacement -GWL.

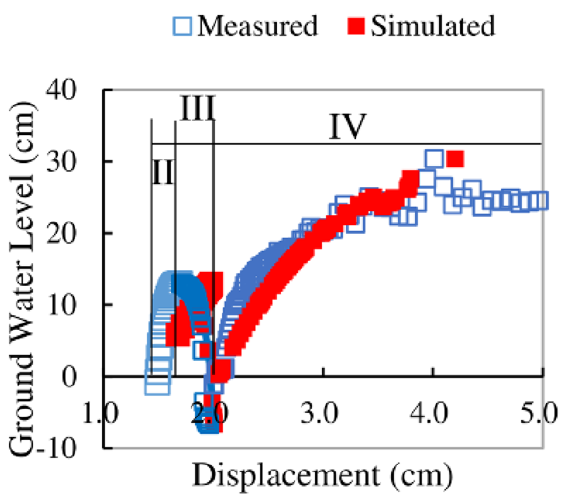

Fig. 2: Comparison of simulated displacement to measured displacement.

REACTIVATION DYNAMICS OF A DORMANT EARTHFLOW DOCUMENTED BY FIELD MONITORING

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Purpose: Earthflows are common landslides in fine-grained materials. A significant feature of these landslides is their complex movement pattern. Earthflows can move slowly for long periods at a rate of less than 1 m/year, primarily by sliding on discrete basal and lateral slip surfaces. However, in response to critical rainfall conditions, they may abruptly accelerate and reach high velocities (up to several meters per hour) for a limited time. Despite the extensive literature on the dynamics of earthflows, field data on the reactivation process are scarce due to the challenge of capturing the critical acceleration phase. This study presents field data documenting the reactivation of a large, dormant earthflow (the Silla landslide) that occurred on February 11, 2014.

Methods: The Silla landslide has been monitored by the University of Bologna for the past 18 years. The monitoring system was part of a general study on the hydrology of clay slopes and run continuously from 2004 to investigate the complex relationship between rainfall and groundwater flow. The system consists of a network of electrical piezometers, 1 rain gauge, and 3 surface wire extensometers installed in the middle and upper part of the earthflow. At the time of failure, 11 pressure sensors were operational. Sensors were nested at various depths using different installation methods such as fully-grouted borehole, ground burial, and conventional open-standpipe. Due to their short response time, the six sensors directly buried into the ground measured the pore-water pressure variations during landslide motion and ground deformation.

Results: The field data indicates that the Silla landslide reactivated rapidly. The initial failure in the source area propagated downslope at a rate exceeding 10 m/hour, resulting in complete mobilization of the 600 m long dormant earthflow in around 60 hours. Although the propagation rate reduced as it progressed downslope, it remained 5 to 20 times greater than the displacement rate observed on the surface. Consequently, the landslide reactivated much faster than it moved. The pressure sensors recorded both the initial response to rainfalls and the subsequent pore-pressure changes due to internal deformation. During the early stage of deformation, when compressional features such as inverse-scarps, shear cracks, and pressure ridges appeared on the slope, the sensors registered positive pore pressure excesses (i.e., hydraulic heads significantly higher than the ground surface), indicating undrained soil compression. As the failure propagated further downslope, the compression quickly turned into extension. All the piezometers showed a pore pressure drop of approximately 5-10 kPa (probably due to the opening of cracks) until the cables broke and the measurements stopped.

Conclusions: The monitoring data collected during the reactivation of a dormant earthflow demonstrate that: 1) the reactivation rate, that is the average rate of downslope propagation of the initial failure, is much faster the displacement rate, that is the average rate at which the landslide moves; 2) the reactivation involves a complex sequence of compression and dilation phases that propagates downslope from the source area.

SESSION 6.5

HYDROLOGICAL MONITORING, MODELLING, AND ANALYSIS OF RAINFALL-INDUCED LANDSLIDES

LOW-COST HYDROLOGICAL MONITORING SYSTEM FOR ASSESSING SHALLOW LANDSLIDE OCCURRENCE ALONG LINEAR INFRASTRUCTURES

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Purpose: Shallow landslides induced by heavy rainfall are a worldwide widespread phenomena and their related hazard is expected to increase due to more intense rainfall as a consequence of climate change (EEA Report No 15/2017). Since 2017, a decision-making tool based on Multi-Criteria Analysis (MCA) has been proposed as an objective approach to obtain landslide susceptibility maps and plan proper remedial works along linear infrastructure corridors (Tamburini et al., 2017). The study of low-cost sensors for Landslides Early Warning Systems (LEWS) as a risk mitigation tool to these phenomena along highways, railways and pipelines is here presented.

Methods: Soil hydrological conditions before a rainfall event for the estimation of trigger moments (Bordoni et al., 2019) are the starting point of a LEWS. Different sensors for the measure of these parameters, particularly soil volumetric water content, exist with different pros and cons. The aim of the research is to compare seven low-cost sensors selected by IMAGEO Srl company together with HORTUS Srl. The sensors have been engineered with a datalogging system and an automatic in-cloud transmission of the data and in June 2022 have been located on field at 2 different depths (-0.6 m and -1.2 m) at the test-site of Montuè in the Northern Apennines (Italy) where an Hydrometeorological Monitoring Station (Andromeda Project) is operating since 2012 with high-cost TDR probes present at the same depths. In November 2022 a volumetric water content profiler with nine measurement depths up to 1 m deep has been added to the new monitoring system. The comparison between the hydrological data acquired by different sensors allows to evaluate the quality and reliability of the low-cost system before its final installation along the infrastructures lines. Monitored data together with rainfall parameters provided by both in situ rain gauges and ERA5-LAND satellite-derived data are used as input for the reconstruction of soil moisture values physically based thresholds.

Results: A first comparation (Figure1-3) between the TDR and low-cost soilvolumetric water content monitored data has been carried out for the period from June 2022 to February 2023.

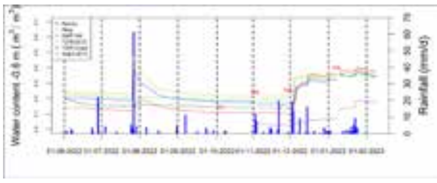

Fig. 1: Montuè soil volumetric water content trend at 0.6 m depth.

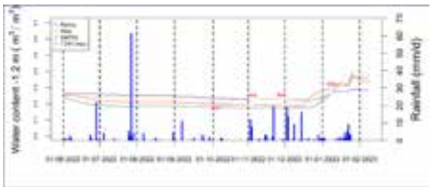

Fig. 2: Montuè soil volumetric water content trend at 1.2 m depth.

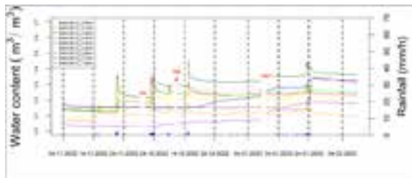

Fig. 3: Montue' soil volumetric water content trend at different depths monitored from the sensor installed in November2022.

Conclusions: The near real-time access to the monitored data allows to send warning alert when the established thresholds are exceeded, resulting in a LEWS able to identify periods of imminent landslide danger and to assess security along the lines.

RELATIONSHIP BETWEEN RAINFALL, WATER TABLE CHANGE AND LANDSLIDE ACTIVITY IN THE SOUTHERN PART OF POLAND

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Purpose: In Poland, instrumental monitoring of over 60 landslides, where the risk of activation is particularly high, has been carried out for over 10 years as part of the Landslide Prevention System (SOPO). The monitoring focuses mainly on landslides located in the southern part of Poland. The area is characterized by scattered settlement, dense road network and high population density. It is a mountainous region forming part of the Outer Flysch Carpathians. Complicated geological conditions and morphology of the terrain result in the occurrence of a large number of landslides. Integration of long-term data on dynamics of displacement, changes in water table and precipitation enables the study and better understanding of the behaviour of these landslides.

Methods: The results of inclinometer measurements, which precisely recorded the depth and speed of rock movement, were compiled for several selected landslides. On each of the analyzed landslides between one and three inclinometer holes were located. Measurements were taken regularly two times a year in the spring and autumn seasons. Piezometric holes were located next to each inclinometer hole, in which changes in the water table were recorded on a continuous basis. Rainfall, the main landslide trigger, was recorded with the use of rain gauges installed on these landslides.

Results: The analysis shows temporal distribution of the dynamics of these landslides in relation to precipitation and geological conditions. In order to expose these dependencies, landslides were divided into two groups. The first group of landslides was located in the areas where the geological substrate is made up of flysch formations with predominance of clay rocks. Landslides of the second group were located in areas with predominance of sandstones in the substrate rocks. Analysis of the 10-year-long record of the observation period shows that, in the areas where the geological structure is dominated by clay, landslides present constant (continuous) activity with displacements not exceeding several mm/year. In the case of areas where the geological substrate is dominated by sandstone, landslide movements were more often abrupt. Dislocations were recorded mainly after spells of intense precipitation or heavy rainstorms.

Conclusions: The performed analysis gives directions and practical advice for designing a landslide monitoring system in specific geological conditions. Monitoring of landslides located in areas with poor rock filtration parameters should include recording of subsurface and surface displacements. In landslides where water filtration is faster, monitoring of the water table changes seems to be a better solution. The variable nature of precipitation and variable geological structure in the analyzed area hinder determination of precipitation thresholds activating landslides.

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DETECTING CHANGES OF REGIME ON AN ACTIVE LANDSLIDE TRIGGERED BY RAINFALL, USING IMPULSE RESPONSE DECONVOLUTION

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Purpose: This study aims at monitoring changes of regime on an active landslide, by computing the evolution of the impulse response displacement caused by rain over time.

Methods: The method consists in computing a nonparametric deconvolution of the impulse response of displacement to rainfall inputs (Le Breton, 2019; Belle, 2014; Bernardie et al., 2015). This is computed over several months of duration, in order to detect changes in the impulse response. The method is applied on the Pont-Bourquin landslide for four years, using rainfall measurements, and displacement measurements based on RFID (Le Breton et al., 2019, 2022).

Results: The method provides a sharper response function than cross-correlation analysis or than the inversion of infiltration-based mathematical functions. Furthermore, it can compute an impulse response over a much shorter time window of data than with the correlation, allowing for impulse response computation on a rolling window (2 weeks at Pont-Bourquin). The impulse response shape and lag time computed at different periods on the Pont-Bourquin landslide, suggest that the landslide response to rain alternates between a stable and transient state (see Figure 1). The lag of the displacement peak occurs 1 and 2.5 days after the rainfall, in the stable and transient state, respectively. And 1 cm of rainfall causes 2.5 and 5 cm of displacement, respectively. The transient state seems to occur every year around August, since 2013.

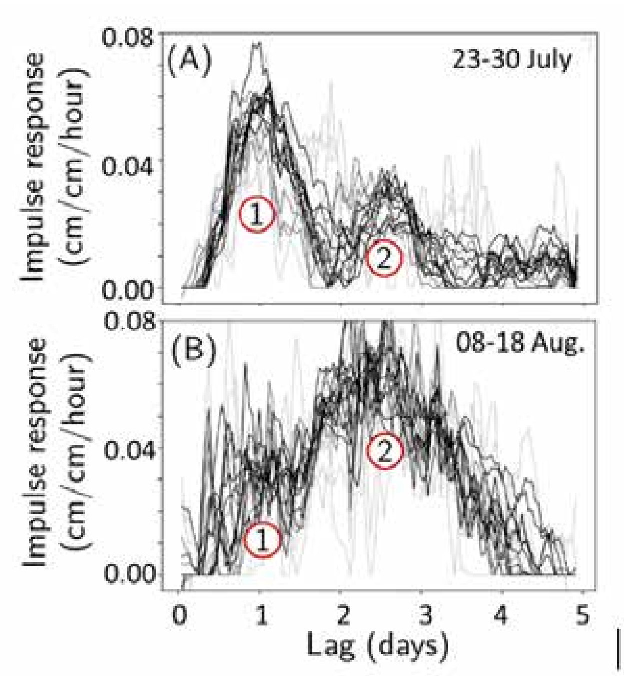

Fig. 1: Impulse response computed at two different periods on the Pont-Bourquin landslide. Each line is a displacement sensor (an RFID tag). The impulse response (A), representing the stable state, presents a faster peak response and a smaller area, than the impulse response (B), representing the transient state.

Conclusions: The impulse response monitoring provides a new method to interpret the processes of a slow-moving landslide that is reactivated by rainfall. It requires only displacement and rainfall data which are very common measurements. However it needs a high enough accuracy and time resolution. The evolution of the impulse response across time would represent a landslide change of state, and a potential precursor to a non-linear rupture.

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COMBINED SEEPAGE-SLOPE STABILITY ANALYSIS OF A CHANNELIZED SLIDE-EARTH FLOW TRIGGERED BY HEAVY RAINFALL

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Purpose: In the mountain environment, rainfall-induced landslides can involve colluvial covers of considerable thickness (5-10 m), which represent remobilizations of channelized deposits resulting from previous slope failures. In these circumstances, the thick colluvial deposit is made up of soils with different hydrological and geotechnical properties and can be characterized by multiple and irregular permeability thresholds that mainly correspond with pre-existing sliding surfaces. In this regard, we investigated a slope failure of a thick stratified colluvial infilling (volume of 40,000 m3) that occurred in the pre-alpine area of the Friuli Venezia Giulia Region (NE Italy), which was triggered by two heavy rainfall events (5 and 12 September 1998) and involved many vineyards close to the Sedilis village. A combined seepage-slope stability analysis was performed in order to simulate the rainfall infiltration process and the related decrease in the slope stability condition.

Methods: The geotechnical model of the Sedilis slide was reconstructed on the basis of extensive data obtained from geological field surveys, boreholes, in-situ measurements and laboratory tests. The combined seepage-slope stability analysis was carried out employing the finite element method and the limit equilibrium method, respectively.

Results: The thick colluvial deposit was formed by two main stratigraphical sequences, deriving from an Eocene flysch rock mass, with different shear strength properties (ϕ1'=35° and c'1=10 kPa; 22°<ϕ2'<25° and 0<c'2<4 kPa) and saturated permeability (K1=10-4 m/s; K2=10-5 m/s). The irregular permeability threshold represented by the basal contact with the underlying bedrock had a strong influence on the water flows within the colluvial deposit at depth. The initial slope stability condition was characterized by a factor of safety slightly higher than FS=1.4, that is far from the critical stability condition. The first analysed rainfall event (5 September 1998: 24-h height of 181.6 mm; maximum intensity of 60 mm/h) caused a localized saturation of the colluvial deposit, and the corresponding decrease in the matric suction resulted in a decrease in the factor of safety of about 20%, without however reaching slope failure. As a consequence of the second rainfall event (12 September 1998: 24-h height of 188.0 mm; maximum intensity of 38 mm/h), the colluvial slope reached the saturation a few days after the rainfall ended, with the onset of pore-water pressures of about 60 kPa that led to slope failure.

Conclusions: The analyzed case-history demonstrates the importance of performing a detailed lithostratigraphic analysis aimed at collecting site-specific soil moisture data to properly define a realistic suction profile at depth, which is key for the subsequent seepage modeling and the related analysis of the slope stability condition. The particular three-dimensional geometry of the colluvial deposit, that infilled a buried pre-existing landslide gully, caused the concentration of rainfall-induced seepage flows as a consequence of the permeability thresholds occurring at depth. This particular geological setting provoked a rapid pore-water pressure increase and a subsequent destabilization of the channelized colluvial slope. The performed back-analysis demonstrates that colluvial slopes with a good initial stability condition can collapse when subjected to close (1-10 days) and intense rainfall events.

INVESTIGATING THE HYDRAULIC RESPONSE OF A SLOPE UNDER DIFFERENT RAINFALL CONDITIONS THROUGH PHYSICAL MODELLING

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Purpose: The purpose of the study is to investigate soil moisture (w) and pore water pressure (pwp) conditions in a small-scale sandy slope model subjected to simulated rainfall of varying intensity and duration, and to evaluate the adequacy of the chosen experimental approach to address various phenomena associated with rainfall-induced landslides, including the transient rainfall infiltration process and hydraulic hysteresis effects on the state of slope stability.

Methods: The experimental setup includes the platform for testing slope models built from uniformly graded fine sand. The soil material was mixed at predefined w and placed using the under-compaction method to obtain 30 cm high slope with 35 degree inclination. While the first model was built directly on the impermeable steel plate, 5 cm of gravel was placed on the bottom of the second model to improve drainage during the test. Slope models were instrumented with theta probes and mini-tensiometers to monitor the hydraulic response, while two high-speed stereo cameras monitored surface displacements of the model.

Results: The changes in volumetric water content (θ) and pwp were obtained for three measurement profiles and several monitoring depths under specifically defined boundary conditions, aimed to provide answers to several questions, such as: how the variation of rainfall intensity affects the hydraulic response of the slope and the time to reach steady-state condition in the unsaturated part of the slope; or to observe possible differences in θ and pwp conditions (also implying differences in slope stability) for steady-state conditions when the same intensity is achieved by increasing or decreasing simulated rainfall. For the material and boundary conditions considered, a significant reduction in matric suction (ua-uw) was observed even at very low rainfall intensities, while changes in w and pwp increased only slightly in the subsequent phase when intensities were increased several times. Moreover, ua-uw never completely dissipated in the monitored points for the well-drained slope model. In contrast to θ-values, ua-uw values were much higher under steady-state conditions when rainfall intensity was achieved by reducing simulated amounts and vice versa.

Conclusions: The promising results of these initial experiments, conducted as part of several ongoing research projects (IPL -256, IPL -265 and uniri-mladi-tehnic-22-62), demonstrate the possibility of using physical modelling to investigate the complex processes that occur in slopes during transient infiltration of rainfall and, in particular, how variations in rainfall intensity and patterns affect the hydraulic response and the state of slope stability. The approach considered could prove valuable in addressing the problem of rainfall-triggered shallow landslides, where the weathered soil cover is typically located above less permeable bedrock, but also in the study of rainfall infiltration and all related phenomena affecting the stability of slopes exposed to infiltrating rainfall in general. Given the interesting results, it is recommended that further experiments be carried out with different geometric conditions, as well as experiments with materials with retention properties that cover a wider suction range and have lower hydraulic permeability, so that more general conclusions can be drawn.

EVALUATION OF THE FAILURE SURFACE AND HYDROLOGICAL INFLUENCE ON GUANGHUA LANDSLIDE BY MATERIAL POINT METHOD

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Purpose: Landslides pose a significant threat to human lives and property. The failure mechanisms are often complicated by various environmental factors, making it challenging to predict the subsequent development and implement effective countermeasures. In this paper, we present a case study of the Guanghua landslide, a large-scale landslide with high activity in Taiwan in 2021, to investigate its failure mechanism and predict its post-failure behavior. On this site, many monitoring data and past landslide activities have been utilized to analyze the landslide's failure mechanism. However, due to the large deformation, subsurface monitoring systems became ineffective, making the behavior of the deep formation unknown. It is necessary to apply numerical models to analyze the depth of the failure surface and predict post-failure behavior. Therefore, we adapted the material point method (MPM), which is used for numerical analysis due to its ability to simulate large deformations and handle complex geometries. The potential application of this study plays an important role in landslide hazards and managing risks.

Methods: In order to investigate the entire failure process, the arbitrary Lagrangian-Eulerian method (ALE method) has been developed for large deformation problems, for example, landslide behavior. MPM is one of ALE's methods and has been utilized in the landslide study recently. Therefore, the aforementioned numerical model was introduced to represent the case study of the Guanghua landslide based on long-term monitoring data. To identify the potential depth of the fractured rock, four geological models with varying depths of the fractured rock were considered in the back analyses. The numerical results were compared with subsurface and ground surface monitoring data for model validation. Furthermore, because the movement in the upper slope was driven by water pressure, a parametric study was performed to evaluate the influence of the rising groundwater level on the movement of the colluvium.

Results: The numerical analysis identified the depth of the failure surface and predicted the post-failure behavior of the Guanghua landslide, revealing that the failure surface developed at a depth of 40-50 m, extending from the upper to the lower slope. This failure band caused the slope to subside at the upper slope and lift up at the lower slope. Moreover, when the sliding masses reached the valley, the overall movement along the deep failure surface could cease due to topographical constraints.

Conclusion: Our findings suggest that a combined approach, involving detailed site investigations, long-term monitoring, and numerical analyses, can significantly improve our understanding of the failure mechanism and provide more comprehensive information for mitigation strategies. This study presents an interesting finding that the large-scale landslide is not always a one-time entire failure, but rather subsequent overall failure can occur after the occurrence of regional failure. Furthermore, terrain plays a crucial role in landslide behavior, as demonstrated by the phenomenon of movement cessation caused by the terrain in this case. These findings are valuable for the development of landslide prevention strategies.

MODELING SHALLOW LANDSLIDES FOR SUSCEPTIBILITY ANALYSIS IN VALTELLINA REGION (NORTHERN ITALY)

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Purpose: During the last decades, the Valtellina valley (northern Italy) suffered from several catastrophic rainfall-induced shallow landslide events inducing debris flows, which caused severe economic losses and casualties. The growing of urban settlements has driven population to colonize areas at risk, where prediction and prevention actions are nowadays a challenge for geoscientists. Debris flows are widespread in mountain areas because occurring along steep slopes covered by loose regolith or soil coverings. In these conditions, heavy rainfall events might cause slope instabilities due to the increase in pore water pressure depending on hydraulic and geotechnical properties as well as thicknesses of soil covers. Despite the initial small volumes, debris flows hazard is significant due to the sediment entrainment and volume increase of the involved material, high velocity and runout distance. In such a framework, predicting timing and position of slope instability as well as paths, volumes, and kinematic parameters of potential debris flows is greatly needed to assess areas at risk and to settle appropriate countermeasures.

Methods: In this work, back analyses of debris flow events occurred in representative sites of the Valtellina valley were carried out based on numerical modeling of slope stability and runout. Susceptibility maps were obtained by a local scale modeling of hillslope hydrological response under specific rainfall conditions, considering the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability (TRIGRS) code (Baum et al., 2008). Unsaturated/saturated hydraulic and geotechnical soil properties were defined considering values from distributed, non-punctual data from SoilGrids maps and bibliographic ones. Runout modeling was performed considering the DAN3D model (Hungr and McDougall, 2009). Involved volumes were derived considering TRIGRS results, SoilGrids thickness data and bibliographic ones. Thickness data were also used to estimate potential maximum thickness of sediment entrainment during propagation. A Voellmy rheological model was adopted and parametrized based on a trial-and-error approach considering available landslides shape.

Results: The analyses allowed the identification of the triggering, transport, and deposition zones of recorded landslides, including other potentially ones (Figure 1).

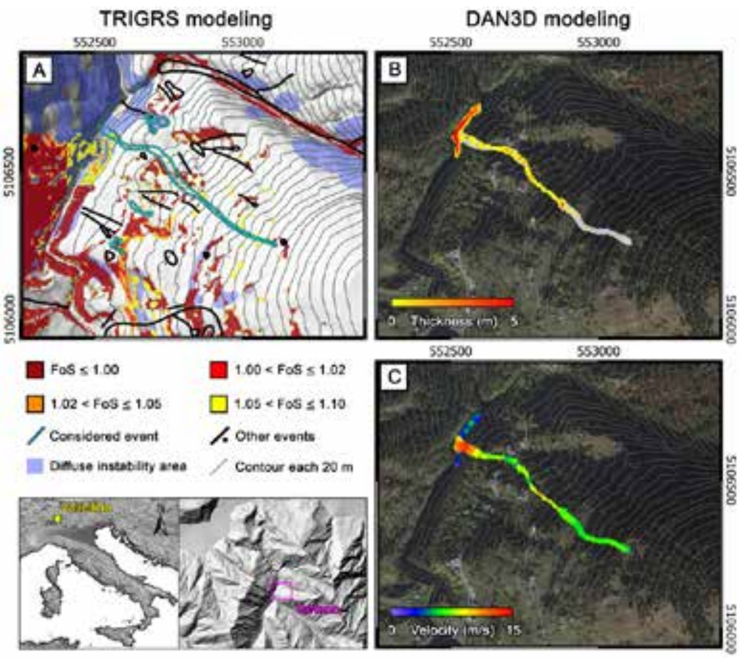

Fig. 1: Example of maps of slope stability (A) and both deposition (B) and velocity (C) obtained by TRIGRS and DAN3D modeling, respectively.

Conclusions: Results from this study emphasizes issues in performing distributed numerical slope stability modeling depending on the availability of spatially distributed soil properties which hamper the quality of physically-based models. In the framework of hazard mapping and risk strategy assessments, the presented approach can be used to evaluate the possible propagation phase of new potential debris flows recognized by geomorphological evidence and numerical modeling. Furthermore, analyses aimed to the probabilistic assessment of landslide spatial distribution, related to a specific value of rainfall threshold, can be considered as potentially applicable to multi-scale landslide hazard mapping and extendable to other similar mountainous frameworks.

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REGIONAL RAINFALL THRESHOLDS OF LANDSLIDE ACTIVITY IN THE POLISH CARPATHIANS BASED ON METEOROLOGICAL AND LANDSLIDE DATA IN THE PERIOD 1996-2020

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Purpose: Landslides are the main geohazard in Poland. Landslide areas and terrains prone to mass movements in the Polish mountains cover more than 2,000 sq km, within which over 60,000 buildings are located. Research on early warning systems is significant for municipalities at high risk of landslides. One of the key elements of these studies is determining the parameters of precipitation - both direct and preceding, which can trigger the movement of earth masses.

Methods: The research includes an analysis of precipitation daily data in the context of landslide activation in the Polish Carpathian region. The aim of the work was to determine the formula defining the relationship of the average intensity of atmospheric precipitation that could cause landslides on its duration (intensity-duration threshold) and similarly the relationship of the total precipitation that could cause a landslide on its duration (total rainfall-duration threshold). The work uses daily precipitation data from 1996 to 2020 from about 300 meteorological stations located in the Carpathian Mountains by the Institute of Meteorology and Water Management, as well as data on the location and date of activation of 481 landslides. The set of landslides was increased by 845 events, for which only the year and month of activation were known, giving the total number of landslide events 1,326.

Results: The first part of the study focuses on the precipitation directly prior to landslide activation. In order to calculate the total rainfall and the duration of each precipitation event, the following definition was adopted: a precipitation event is a sequence of precipitation, preceded and ended by 6 "dry" days, in which the total rainfall was not more than 6 mm, with the exception that for landslide precipitation event the end date was the activation date. On the basis of daily precipitation data, 115,637 of all precipitation events that took place in the Polish Carpathian region in the years 1996-2020 were calculated. Each event was assigned the values E (total rainfall), D (duration), and I (average rainfall intensity). The table of precipitation events was enlarged by 1,326 events that caused a landslide. Furthermore, the table of all precipitation events (causing landslides and not) allowed for determination of I-D and E-D relations, leading to the estimation of direct precipitation thresholds. The second part of the research was focused on examining the correlation between the parameters of precipitation preceding the activation of landslides (rain from the previous 12-18 months in different time intervals and with different parameters) as well as geological parameters of the landslides themselves. The parameters showing the best correlation were used to select additional criteria for thresholds of direct rain that could trigger a landslide.

Conclusions: This preliminary determination of rainfall thresholds is part of the research that is to result in the construction of an early warning system for landslide risk in Poland.

BACK-ANALYSIS OF CATASTROPHIC EVENTS FOR LANDSLIDE STABILITY MODELLING AT CATCHMENT SCALE

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Purpose: The development of smart strategies for geo-hazard management in urban areas has lately become crucial in relation to the higher occurrence of extreme events, expected as a consequence of climate change. In this work, a novel hydrological model from Politecnico di Milano (SMART-SED) is applied to different Italian catchments for the back-analysis of catastrophic events occurred in past and in recent times. The present physically-based model was initially developed for the evaluation of erosion and sediment transport, but it was recently improved for slope stability analysis. The advantages of SMART-SED with respect to other similar models are the automatic detection of the drainage zones, the statistical downscaling of soil granulometry input maps and the evaluation of the factor of safety at catchment scale. Moreover, the input data required are few and they are usually open data.

Methods: After a calibration phase, the erosion and the sediment transport processes implemented inside SMART-SED were successfully validated thanks to the availability of sediment transport data over time in catchments characterized by different bedrocks in the Italian Alps and in the Apennines. Then, a new module for the slope stability assessment was added, considering the Montgomery & Dietrich approach and the Harp 2006 model. Afterwards, the back-analysis of some well-known Italian floods and debris flows cases was accomplished, considering as input the relative extreme rainfall data, in order to understand the capabilities of the improved model. The first case study analyzed was the one of Valtellina 1987 (northern Italy), which developed several shallow landslides and debris flows, for example, in the Tartano lateral valley. Also, the flooding event of Misa river in Senigallia 2022 (central Italy) was analyzed. Moreover, simulations with precipitations regimes from the General Circulation Model climate change projections were performed to understand possible future hazard scenarios. A comparison of the results with field evidences was then considered for rainfall thresholds evaluation in a changing world.

Results: The back-analysis shows a good performance of SMART-SED for the identification of the unstable slopes. In particular, the source areas of the debris flows of Tartano 1987 are correctly recognized. In addition, the model quantifies the erosion amount, the river discharge and the sediment transport related to that event. Also the resulting flooded areas in Senigallia were considered accurate, based on their comparison to the real flooded areas mapped by Sentinel Hub. Finally, the simulations of the climate change scenarios show an increase of the magnitude of solid and water discharge that has to be taken into account for the adaptation of the actual rainfall thresholds to the future rainfall regimes.

Conclusions: The SMART-SED model was successfully tested to catchments with different geological frameworks for the back-analysis of past catastrophic events and it proved its reliability for the evaluation of water discharge, sediment transport and slope stability assessment. A complete hydrological model under the point of view of the natural processes simulated can represent an innovative tool for urban planning and risk mitigation in a climate change scenario.

SESSION 1.9

LANDSLIDES AND OTHER GROUND FAILURES TRIGGERED BY THE FEBRUARY 6, 2023 M7.7 AND M7.6 TURKEY-KAHRAMANMARAS EARTHQUAKES

GENERAL CHARACTERISTICS OF THE 6 FEBRUARY 2023 KAHRAMANMARAŞ-TÜRKIYE EARTHQUAKE SEQUENCE

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East Anatolian Fault Zone (EAFZ) is on the plate boundary between the Arabian Plate and Anatolian Block, and is an approximately 450 km long, North-East trending left-lateral strike-slip fault system. It connects to the North Anatolian Fault Zone (NAFZ) at the Karlıova junction and extends to the city of Hatay in southeastern Türkiye. The high of level of seismicity on the fault zone is governed by the northeast displacement of the Arabian plate at a rate of 11 mm/year relative to the Anatolian Block. Along the EAFZ, despite some seismically quiet segments for decades, many segments failed within the period of 1700-1900. These seismic gap segments were activated and ruptured during Bingöl (Ms=6.8), Malatya-Doğanşehir (Mw=6.1),Bingöl-Çimenli (Mw=6.4), Elazığ-Karakoçan (Mw=6.0), Elazığ-Doğanyol (Mw=6.7) earthquakes in 1971, 1986, 2003, 2010, and 2020, respectively. The southern segments including Erkenek, Pazarcık, Amanos, Antakya, Çardak and Sürgü had stayed as the quiet segments, and continued to buildup elastic strain energy, until the recent earthquake sequence. Along the Erkenek, Pazarcık and Amanos segments, a Mw=7.8±0.1 Kahramanmaraş-Pazarcık earthquake occurred on February 6, 2023, 01:47 UTC. The event initiated first on Narlı fault in the south, and stepped over to the Pazarcık-Erkenek segments. It ruptured towards both north-east and south-west by exhibiting a bilateral rupture mechanism, rupturing the Amanos segment in the southwest. Approximately 9 hours later at 10:24 UTC, a Mw=7.7±0.1 Kahramanmaraş-Elbistan earthquake occurred near Ekinözü due to rupture of the Çardak and Sürgü segments. The provinces of Kahramanmaraş, Adıyaman, Hatay, Osmaniye, Gaziantep, Kilis, Şanlıurfa, Diyarbakır, Malatya, Adana, and Elazığ, located in south-eastern Turkiye were significantly affected by the events. The reported life losses exceeded 50,000. Over 250,000 buildings were determined as collapsed or severely damaged; hence over 2 million people were faced with accommodation problems. The economic damage is estimated as over 50 billion USD. In addition to damages on the buildings and the infrastructures, liquefactions, landslides, rockfalls and rock avalanches were also triggered by the earthquake sequence. The purpose of this study is to describe the general seismotectonic characteristics of the 6 February 2023 Kahramanmaraş earthquake sequence, employing geological and seismological data along with field observations.

INVENTORY OF THE ROCKFALLS TRIGGERED BY 6 FEBRUARY 2023 TÜRKIYE EARTHQUAKES AND THEIR POSSIBLE MECHANISMS ALONG FEVZIPAŞA-ISLAHIYE RAILWAY SECTION

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Two large earthquakes occurred on 6 February 2023 along the East Anatolian Fault Zone (EAFZ). During the Mw=7.8±0.1 Pazarcık earthquake, the Erkenek, Pazarcik and Amanos segments ruptured and approximately 300 km surface rupture occurred. The Fevzipaşa – Islahiye Railway Section is located along the eastern slopes of the Amanos Mountains. The surface rupture of the Amanos segment extends near Fevzipaşa – Islahiye Railway Section. This section was constructed in 1930s and it connects Fevzipaşa to Tahtaköprü (south border of Türkiye). Approximately 2 km part of this railway section is completely damaged by extensive rock slope failures and rockfalls. Along the section, a rockfall and rock slope failure inventory was prepared and possible causes are discussed. In this part, the Middle Jurassic – Createcous aged neritic limestones forms the lithology. The limestones are jointed but discontinuity spacing is occasionally very large. For this reason, the limestones have very large blocks. The slopes of the railway in this section were designed as 75-80 degrees. Some parts of the engineering slopes were protected with steel mesh against rockfall. However, some rock blocks fell on the railway from the higher altitudes. In addition, some serious rock slope failures controlled by discontinuities were triggered by the earthquake. In this study, the inventory of the rockfalls and rock slope failures is given and their mechanisms are explained. These explanations may help to predict similar future hazards.

LANDSLIDES TRIGGERED BY THE FEBRUARY 6, 2023, TÜRKIYE EARTHQUAKE SEQUENCE AND THE FOLLOWING RAINFALL EVENTS

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The devastating earthquake sequence occurred on February 6, 2023 within the East Anatolian fault system. Two main shocks, estimated as Mw 7.7 and Mw 7.6 by the Kandilli Observatory and Research Institute, occurred nine hours apart and affected 10 cities and subjected an area >100,000 km2 to shaking levels known to trigger landslides (PGA >8%g). Approximately a month after the earthquake sequence, the majority of the area was also hit by intense precipitation events, which further remobilized loose co-seismic landslide deposits and caused some fatal debris flows.

In the days immediately following the earthquake, we examined high-resolution satellite images and aerial photos and used other remote sensing techniques (e.g., InSAR, change detection) to search for landslides of particular concern for human safety and to provide situational awareness to authorities. We also sought to gain better insight into this co-seismic landslide event and its possible post-seismic consequences. This remote campaign was supplemented a few weeks after the earthquake by field surveys of landslides of concern. Here we present the preliminary findings of these investigations.

Our observations showed that the earthquake sequence resulted in numerous co-seismic landslides, especially in the north. Surface rupture through mountainous terrain caused some big and sometimes fatal landslides. Rock fall is the most widely observed co-seismic landslide type though we also noted bedrock rotational, planar slides, lateral spreading, and rock avalanches. Lithology, spatial variability of ground shaking, topographic relief, and the arid/semi-arid climatic conditions appear to be the main variables controlling the spatial distribution of the observed co-seismic landslides. Intense ground shaking strongly deformed and damaged many hillslopes and mobilized some deep-seated landslides, so in the post-seismic period, we expect that heavy rain and snowmelt may result in a considerable number of additional failures and deformation on those hillslopes. Therefore, long-term monitoring may be needed to understand the earthquake legacy effect and post-seismic hillslope response.

IMPACT OF VARIOUS GROUND FAILURES TRIGGERED BY THE 6 FEBRUARY 2023 KAHRAMANMARAS (TÜRKIYE) EARTHQUAKES ON NATURAL GAS PIPELINES

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The ground failures induced by the Kahramanmaras 7.7 Mw and 7.6 Mw earthquakes occurred on February 6th 2023 influenced ten provinces covering approximately 100,000 km2 with over 12 million inhabitants. Besides the losses of lives and damages to settlements, critical infrastructure was also heavily affected. The damages of the infrastructure such as roads, viaducts, railways, power grid, dams, natural gas and oil pipelines, etc. also caused accidents, hindered the emergency response, and disrupted daily life in most cities and towns. BOTAŞ Petroleum Pipeline Corporation operates natural gas and oil pipelines in Türkiye. There are approximately 2200 km of natural gas pipelines and 1700 km of crude oil pipelines in the area, and several damages (ca. 24) to the natural gas pipelines were reported after the Kahramanmaras earthquakes. All facilities where natural gas and crude oil activities are carried out were designed, constructed, assembled, tested, controlled, commissioned, operated, maintained, and repaired while ensuring a minimum level of safety in accordance with the European Standards (EN), Turkish Standards (TS), Turkish Standards Institute (TSE), International Standards Organization (ISO), International Electrotechnical Commission (IEC), American National Standards Institute (ANSI), American Society of Mechanical Engineers (ASME), American Gas Association (AGA), American Petroleum Institute (API), German Standard Institute (DIN), and National Fire Protection Association (NFPA) standards. Although the design principles for site selection and construction methods were properly applied considering even fault crossing, the devastating effects of the event showed that the influences of geohazards need to be analyzed to potentially revisit the relevant codes. A preliminary analysis of the accidents showed that the types of post-earthquake ground failures yielded the destruction include landslides, lateral spread, liquefaction and fault flowering (Figure 1). This study aims to provide an in-depth analysis of the ground failures and the damages they caused on the natural gas pipelines. In addition, as more than two thousand landslides were triggered by the earthquakes in the region and a number of them harmed natural gas pipelines, susceptibility maps for analyzing their spatial probability distribution were produced in this study using novel machine learning algorithms. The results will be jointly analyzed with earthquake susceptibility maps, liquefaction, and further geological characteristics of the region in order to reveal their usability for an improved disaster management under similar conditions.

Fig. 1: Aerial images from the natural gas pipeline damages sourced from landslides, fault flowering, liquefaction and lateral spread. Aerial image credit: HGM Küre platform of General Directorate of Mapping, Türkiye.

CHALLENGES FOR A RELIABLE ASSESSMENT OF LANDSLIDES IN SEISMIC MICROZONATION STUDIES: THE CASE OF THE DAUNIA APENNINES, ITALY

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Landslides and earthquakes represent two major geohazards in Italy and, in particular, in the seismically active Apennine Mountains where low strength lithologies are common. In various countries throughout the world, the development of affordable and effective earthquake risk reduction approaches relies on the production and application of detailed-scale seismic microzonation maps (seismic hazard maps) with reliable estimates of the expected ground motion.

In Italy, such maps are currently being produced for hundreds of cities and towns at the 1:5000 scale, to properly account for the influence of local geological-geomorphological setting (site effects) on the ground shaking intensity, as well as for the presence of local-scale seismically-induced ground failures (e.g., landslides, liquefaction). In this work, we discuss the experiences gained in the seismic microzonation investigation of the south-eastern part of the Apennines called the Daunia Mountains, which extends for about 1500 km2 and includes many small hilltop towns.

Rainfall-induced slope failures are common in this area, while historical evidence of the seismically-triggered landslides is scarce and apparently consistent with the infrequent occurrence of medium-large magnitude earthquakes. However, hundreds of ancient very large (>2X105 m2) landslides are documented in the new multi-temporal landslide inventory of the Daunia Mountains. Some of these landslides involve peri-urban hillslopes and few have been urbanized. Their age is unknown, but they appear distributed near the known seismogenetic sources of M>6 events and tend to originate at upper hillslopes.

Numerical analysis of selected large ancient landslides indicates that the host slopes are unlikely to fail unless artesian groundwater pressure is considered. Though challenging, the origin and age of the very large slope failures in Daunia Mts. should be ascertained given the implications for the seismic hazard zonation of the area.

Acknowledgements
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16 NOVEMBER 2023

SESSION 2.9

PAST, PRESENT AND FUTURE OF SATELLITE INTERFEROMETRY FOR LANDSLIDES (part I)

REGIONAL TO NATIONAL SCALE MAPPING OF ACTIVE SLOW-MOVING LANDSLIDES BASED ON THE EUROPEAN GROUND MOTION SERVICE PRODUCTS

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Purpose: European Ground Motion Service (EGMS) products provide ground motion velocity and displacement measurements over the Copernicus Participating States. The millimeter accuracy products consist of processed Sentinel-1 SAR images with the Multi-temporal Differential SAR Interferometry algorithms and are available for visualization and download. Access to the EGMS data opens up many capabilities for various fields of interest, including landslide monitoring and assessment. Landslide inventory creation and continuous monitoring of landslides are crucial actions for hazard evaluation and risk mitigation of this process. However, their mapping and creation are still an issue for many countries, scenarios where EGMS measurements are a much-needed resource to overcome these problems. We aim to exploit these resources to successfully identify the areas with active landslides and create a homogenous inventory at a desirable national scale.

Methods: The EGMS offers three measurements for February 2015 - December 2021: velocity and displacement time series for ascending and descending orbits, the derived displacement vectors for the vertical and horizontal E-W components, and the projected vector along the lope. In our case, we used the non-parametric Mann-Kendall test on the displacement times series LOS measurements to objectively evaluate the areas showing a consistent deformation trend. With its help, it was possible to identify the PS points characterized by a temporal trend of displacements and calculate the linear trend's slope. These variables evaluate the magnitude of deformation and allow the automatic filtering of the PS measurements for landslide-related deformations.

Results: The initial results show promising perspectives that will increase the potential of such data. While testing the approach at the local scale for computational purposes, we successfully identified clusters of points associated with landslide deformations. Moreover, considering the velocity threshold proposed by Cruden and Varnes (1996), the identified displacement hot spots are classified into slow-moving or extremely slow-moving landslides.

Conclusions: The proposed method allows a rapid assessment of deformations associated with slow-moving landslides. It sets the basis for further investigations, including permanently monitoring critical areas and developing an early warning system for these landslide types.

THE EUROPEAN GROUND MOTION SERVICE FOR UPDATING THE ITALIAN LANDSLIDE INVENTORY

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Purpose: The present work aims at analysing satellite interferometric data of the European Ground Motion Service - EGMS with respect to the Italian Landslide Inventory (Inventario dei Fenomeni Franosi in Italia – IFFI) in order to evaluate the potential of EGMS Sentinel-1 data to update the state of activity of extremely to very slow landslides recorded in the national Inventory, and identify new landslides not yet mapped, through the identification of active deformation areas.

Methods: The EGMS provides ground deformation products at pan-European level with millimetre accuracy. The EGMS is based on a multi-temporal interferometric analysis of Sentinel-1 radar images at full resolution. This technique allows identifying reliable measurement points (e.g. buildings, artificial structures and non-vegetated areas) for which LOS velocity values and time series of deformation are extracted. The service provides data from February 2015 to December 2021. Two annual updates are planned for 2022-2023. The Italian Landslide Inventory, carried out by ISPRA and by the Regions and Autonomous Provinces, contains more than 620,000 landslides affecting an area of 23,700 km2, equal to 7.9% of the Italian territory. Temporal coverage of the landslide dates of occurrence is from 1116 to 2022. Each landslide is represented by a point (Landslide Identification Point) located at the landslide crown, and by a polygon for 84% of landslides. Inventory data are updated through the IdroGEO web platform. 27% of the Italian landslides are rapid movements (rockfall/topple, rapid debris flows and areas affected by rockfall/topple) not detectable by InSAR data processing. On the other hand, 13% classified as slow earth flows, 0,35% as Deep Seated Slope Deformation (DGPV) and a part of the complex landslides and rotational/translational slides are suitabile to be monitored with satellite Interferometric technique.

Results: Statistical analyses on the Ascending and Descending orbits measurement points falling within the polygons of the IFFI Inventory have been carried out: number and density of measurement points; minimum, average and maximum velocity and relative standard deviations; number and percentage of moving measurement points. Other variables that have been taken into account are type of movement, slope orientation with respect to acquisition geometry of Sentinel-1 and land use/land cover.

Conclusions: Processing results on a large dataset have better pointed out which landslides can be monitored with satellite data and therefore can be updated in the IFFI inventory. Those data could be viewed on the IdroGEO web platform, within the GeoSciences Research Infrastructure under implementation by a PNRR project funded by the Ministry for University and Research with Next Generation EU funds.

A LARGE-SCALE SATELLITE INTERFEROMETRIC OBSERVATION AND ACTIVITY ASSESSMENT OF DEEP-SEATED LANDSLIDE IN TAIWAN

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Global climate change has intensified the occurrence of extreme rainfall events, resulting in frequent slope disasters and significant loss of life and property, in recent years. To rapidly and precisely locate disaster-prone slopes and assess the activity thereof, Central Geological Survey (CGS) has previously identified over 9,000 deep-seated landslide (DSL) sites using the LiDAR technology; and the Soil and Water Conservation Bureau (SWCB) has selected 269 sites therefrom based on their respective scale of potential impacts and significance of protected targets. With an integrated use of LiDAR, InSAR, GNSS and other technologies, this study aims to effectively select DSL areas with a high susceptibility or activity as hotspots. We have adopted JAXA ALOS-2/PALSAR imagery and InSAR technique to process the long-term deformation of study areas. Next, optical satellite images and high-precision digital elevation models (DEMs) are used to visually present a computer-based morphometric analysis and construct micro topographical images of the study areas in order to identify and determine landslide triggering factors. Finally, based on the grading standards of Landslide Activity Index (LAI), slopes with high activity and detailed monitoring are selected to proceed with a regression analysis on rainfall and potential sliding areas in order to discuss the overall landslide movement pattern and failure mechanism.

We have produced surface deformation data of 269 sites based on the satellite data collected between 2020 and 2021; and, with the use of geometric relationship, converted Line of Sight (LOS) to displacement along the slope direction of DSL. In addition, the natural breaks classification (NBC) method has been adopted to set up the activity index and rank the said sites based on their average surface deformation rate. According to the analysis results, 47 sites have high activity (17%), 77 sites have medium activity (29%) and 145 sites have low activity (54%). Among the sites with high activity, 32 of them are within the jurisdiction of SWCB and information related thereto are provided to SWCB for the following research as priority. 10 DLS with a high susceptivity have been selected to produce time-series surface deformation based on satellite images collected between 2015 and 2021; and the data are then used to identify potential sliding areas of these sites and proceed with a rainfall regression analysis. The results indicate that the colluvium and seasonal rainfall of the most of high-risk DSL areas have a high positive correlation. Also, we have carried out maintenance works on corner reflectors installed in two DSL areas and used the Multi-temporal InSAR (MTInSAR) technique to produce cumulative surface deformation data, which are written in quarterly reports with maintenance records. The monitoring results indicate that Site D066 has signs of side erosion at the toe and the slippage can reach -35 mm; and that the toe on the right of Site D077 appear to slide along the slope and the slippage can reach -45 mm. And finally, the surface deformation generated using the InSAR technique are integrated into the open platform of “DSL Monitoring Database and Integrated Inquiry System” to provide SWCB with future reference and to facilitate future applications related to disaster prevention and mitigation plans and land management.

MULTI-FREQUENCY SATELLITE RADAR INTERFEROMETRY DATA PROCESSED WITH MULTIPLE TECHNIQUES FOR LANDSLIDE MAPPING AND MONITORING: PART OF THE ITALIAN SPACE AGENCY'S MEFISTO PROJECT OUTCOMES

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Purpose: In the last two decades, satellite Multi-Temporal InSAR (MTInSAR) techniques became consolidated tools for studying slow landslides. The availability of satellites that use different SAR band frequencies and the development of processing algorithms have constantly improved. One of the main aims of the Mefisto project(1) of the Italian Space Agency (ASI) was to test the potentiality of multi-frequency (X, C and L bands) MTInSAR data processed with different methodologies applied to a multi-scale slow landslide analysis.

Methods: Multi-sensor exploitation was planned, using datasets from Sentinel-1 (C-Band) and Cosmo-SkyMed (X-Band) satellites. A preliminary analysis of L-Band SAOCOM is also under investigation, despite the small number of available images. A two-step strategy was adopted based on a small scale (low-resolution) analysis followed by a high-resolution processing. Two different high-resolution processing were considered: one implemented at full resolution, via tomographic approach (specifically DTomoSAR in Fornaro et al., 2014), and the other on the CAESAR algorithm (Verde et al., 2020) that allows increasing the spatial density of measurement points on sparsely vegetated areas. Post-processing procedures were applied to obtain complementary information (e.g., the resolved velocity (EW and Vertical) vectors or the projection along the slope (VSlope)).

Results: The Sentinel-1 data processed with DTomoSAR allowed for updated landslide movement over large areas. It was possible to classify the activity state and its spatial distribution of about 60% of the deep-seated gravitational slope deformation (DsGSDs) in the Valle d'Aosta Region (Northwestern Italian Alps) (Figure 1A). The Sentinel-1 data processed with CAESAR showed good data density performance on a low-vegetated area (e.g. talus or debris) compared to DTomoSAR (Figure 1B), allowing for an increase in detectable landslides. The combined use of the Sentinel-1 datasets acquired over ascending and descending orbits, processed by CAESAR algorithm, and their post-processing products allowed us to map with high-detail geostructural sub-sectors of some selected DsGSDs (Figure. 1C). The Cosmo-SkyMed dataset provided accurate landslide displacement and time series mapping, allowing for correlation with damages to buildings in the village of Mendatica (Ligurian Alps, Italy) (Figure 1D).

Conclusions: The results of the Mefisto project confirmed that a multi-frequency InSAR approach is suitable for investigating diverse slow slope instability phenomena and the study areas' characteristics. Its potential ranges from large scale DsGSD activity assessment using free and open data of C-band satellites (e.g. Sentinel-1), to high-resolution X-band satellites able to track single-building displacement and damages over landslides that affect worldwide villages in mountain areas.

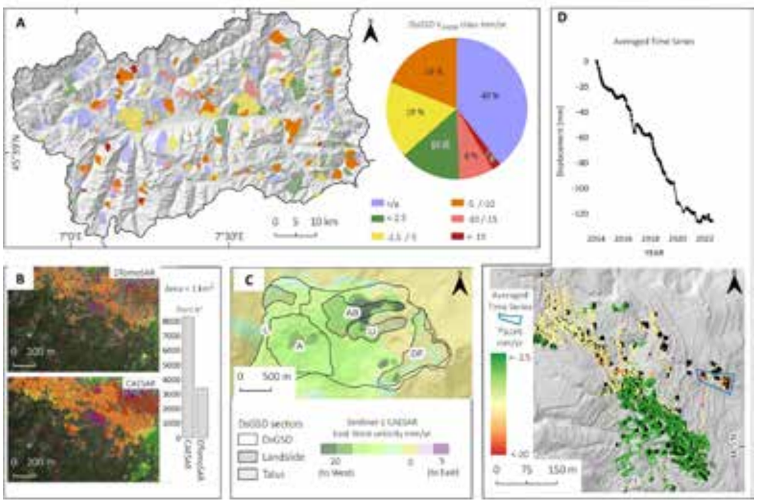

Fig. 1: A) State of activity classification of DsGSD in Valle d'Aosta Region based on Sentinel-1 DTomoSAR; B) Data density comparison between DTomoSAR and CAESAR; C) Mapping DsGSD sub-sectors using East-West interpolated velocity; D) Vslope and time-series of the Cosmo-Skymed dataset over the landslide affecting Mendatica village.

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2. Verde et al. 2020 https://doi.org/10.1109/TGRS.2020.3007927

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SLIDING GIANTS: INSAR MONITORING OF LARGE FOSSIL LANDSLIDES IN DESERT ENVIRONMENTS

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Purpose: Giant terrestrial landslides (V>108 m3) usually occur in the steepest, deeply incised and formerly glaciated landscapes, flank of volcanos, and tectonically active mountain belts. Seismic activity, volcanic eruptions and heavy precipitation trigger nearly two-thirds of these kilometre-scale large slope failures. However, some large-scale landslides have been observed in extremely low-relief landscapes along the steep plateau margins in hyper-arid desert environments. Although it is generally accepted that cliff cuts in arid regions retreat as a consequence of pediment formations under present-day arid conditions, there has been no consensus about the primary mechanism involved. It also remains unclear whether some of these landslides intersecting with these escarpments are still active and whether the movement is slow or catastrophic.

Methods: We have investigated slow-moving mega paleo landslide complexes situated in hyper-arid regions on three continents. The three areas have varying environmental and geological settings. The study sites are located along the boundaries of the Ustyurt Plateau in Central Asia, the Messak Plateau in Central Sahara, and Patagonian Plateau in Argentina. Our studies are based on wide-area InSAR processing of Sentinel-1 data.

Results: The landslides predominantly manifest as continuous fringes of escarpments extending hundreds of kilometres in length and up to five kilometres in width, developed along and around the plateaus across all three locations. Several morphological indicators obtained from VHR satellite images and digital terrain analysis and InSAR data provide evidence that the failure mechanism can be best described by a combination of translational and rotational sliding. Such landslide processes developed on nearly horizontal slopes were seen in all three plateaus where brittle rocks overlie weak and more ductile layers. The weak clay-rich and siltstone layers become more ductile as a result of water seeping through the system of fractures, accelerating the movement of the blocks. Additionally, the creeping of the gypsum and salt which form the interbeds is another contributing factor when water penetrates the system.

Conclusions: We analyze the present-day evolution of these giant fossil landslides in a spatiotemporal extent and relate their formation mechanism with the lithology and past climate change in a Quaternary context. The findings also shed light into the escarpment evolution by subparallel slope retreat under the present-day arid conditions.

REMOTE SENSING AND FIELD RECONNAISSANCE OF EARTHQUAKE INDUCED LANDSLIDES

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Purpose: Earthquake-induced landslides have both short-term and long-term impacts, the former immediately disrupting buildings, infrastructure and earthquake emergency response, and the latter affecting the landscape. This research evaluates the applicability of remote sensing techniques to firstly assess the immediate impact of earthquake induced landslides, using the Haiti 2021 earthquake as a case study, and secondly assessing longer term landscape changes following the Nepal 2015 earthquake. The latter is important as it can inform likely locations that may fail again in subsequent triggering events.

Methods: Optical and Synthetic Aperture Radar (SAR) imagery are commonly used to assess the impact of landslides shortly after an earthquake. While the use of optical imagery can be limited by cloud coverage, SAR sensors provide all-weather night and day observations, thanks to their cloud penetration capabilities. Recently developed approaches use the variation of signal backscatter intensity to identify changes on the ground surface that can be correlated with earthquake-induced landslides. To assess the impact of earthquake-induced landslides, a combined approach based on Sentinel-1 SAR data and a training dataset of landslides mapped using optical Sentinel-2 imagery was used to delineate and classify regional-scale landslides caused by the 2021 Haiti earthquake. To evaluate long-term landscape change following the 2015 Nepal earthquake, Landsat optical imagery over a period of 5 years (2015-2020) was utilised to map landslide occurrences. Results were validated by field reconnaissance undertaken in 2019 and 2022.

Results: Figure 1a shows optical Sentinel-2 pre-earthquake imagery with Figure 1b showing the post-imagery highlighting the earthquake-induced landslides triggered by the 2021 Haiti earthquake. An initial attempt to use unsupervised learning to classify the optical imagery to identify the landslides (Figure 1c) was adversely impacted by dense cloud cover. However, Sentinel-1 Amplitude Ratio imagery (Figure 1d) can be seen to successfully identify landslides, including some missed by manual mapping of the optical imagery. Analysis of Landsat optical imagery following the 2015 Nepal Earthquake identified that enhanced landslide activity only occurred for a short duration, with reactivation of the landslides occurring for only 2-3 years. This was confirmed by field observations in 2018, 2019 and 2022 (Figure 2), with many landslides becoming highly revegetated with limited evidence of reactivation during subsequent triggering events.

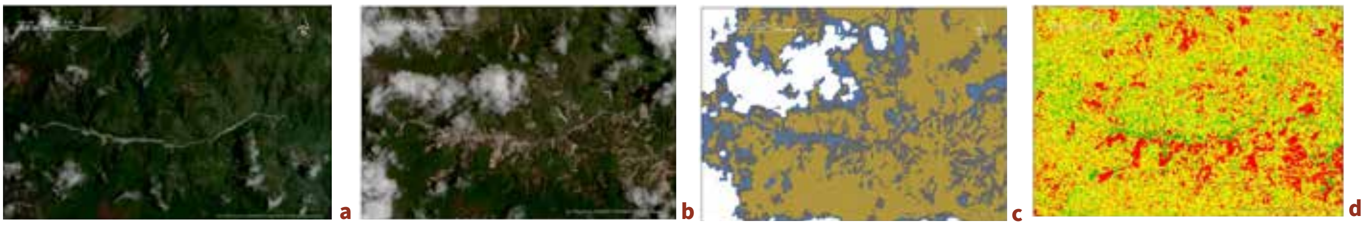

Fig. 1: a) Pre- and b) post-earthquake Sentinel-2 imagery following the 2021 Haiti Earthquake; c) Sentinel-2 classified imagery; d) Sentinel-1 Amplitude ratio imagery

Conclusion: The findings from the study identify that SAR imagery can be an effective tool to evaluate the impact of earthquake induced landslides following an event. However, results are required to be validated, and test samples obtained from Sentinel-2 optical data can be used for this purpose. The combined approach can be an effective post-event tool and support earthquake recovery. In addition, optical imagery is an effective tool for evaluating the long-term impact of earthquake induced landslides on the landscape, thus supporting a better understanding of the susceptibility to future earthquake- and rainfall- induced landslides.

Fig. 2: Example of revegetated earthquake-induced landslides following the Nepal 2015 earthquake, mapped in 2019 and 2022.

MULTI-TEMPORAL INTERFEROMETRIC ANALYSIS OF LANDSLIDES AFFECTING UTTARAKHAND MOUNTAINOUS REGIONS, INDIA

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The present project has been developed in the context of Swiss Development Cooperation Global Programme Strengthening Climate Change Adaptation in Himalayas (SCA-Himalayas).

This project is aimed on mapping land deformation affecting several mountainous area in the Uttarakhand Indian State. To this end, Synthetic Aperture Radar (SAR) data are analyzed exploiting the capabilities of Remote Sensing techniques, and particularly multi-temporal analysis of SAR data, on providing information about instability evolution on different sites, characterized by different scale. In particular, 3 cases are analyzed: Nainital and Joshimath municipalities and Bhagirathi valley, from Rishikesh to Gangotri.

The analysis is focused on Sentinel-1 SAR data, acquired by ESA. The mission started in October 2014, with a 12-day revisiting time. The ground resolution of Sentinel-1 SAR images is 15 meters. In Uttarakhand two different acquisition geometries are available, ascending and descending. The SAR acquisitions have been processed using the most common algorithms to derive the temporal evolution of surface deformations, specifically Persistent Scatterers (PS) and Small Baseline Subset (SBAS). Considering the variation in time of the backscattered signal phase of multiple acquisitions, these techniques allow to measure surface deformations, along the satellite Line-Of-Sight. It is possible to retrieve deformation with a millimeter sensitivity and measure the deformation rate over the selected temporal interval.

The analyzed areas are characterized by strong variety in terms of elevation, geo-morphology, vegetation density, snow cover periods, rainfalls, …

Results, consisting of deformation velocity maps, identified some localized areas affected by landslide characterized by slow dynamics, affecting houses and building, low vegetated slopes, and eventually some streets.

The great power of these techniques on retrieving the temporal evolution of deformations is particularly interesting as this allows to identify variable trends, acceleration and oscillation, correlated with rainfalls or other with triggering factors.

The deformation maps obtained as the output of this analysis could be used basemap to identify some ongoing slow deformations.

Generally, working at local scale was helping on extending the spatial coverage of final results. In addition, for the recently reactivation of Joshimath landslides, the deformations happened in January 2023 were large enough to be measured through differential interferograms.

All the obtained information could be of great use as an auxiliary information on the generation of landslide susceptibility maps as well as to update the activity information on the existing catalogues.

Acknowledgements
The authors gratefully acknowledge Swiss Development Cooperation (SDC) that supported sarmap analyses in the framework of the project “Strengthening Climate Change Adaptation in Himalayas (SCA Himalayas) ”.

IDENTIFICATION OF UNSTABLE SLOPES IN MEDELLÍN (COLOMBIA): FIRST RESULTS FROM SENTINEL-1 INSAR

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Purpose: Medellín (Colombia), the second-largest city in Colombia, is located in a deep and relatively narrow intramountain valley characterized by steep terrain and high levels of rainfall, making it susceptible to landslides. The city has experienced several major landslides in recent decades, which have caused significant damage and loss of life, highlighting the great importance of effective landslide monitoring and management in a city also exposed to an intermediate seismic hazard. Many neighborhoods of the city are characterized by informal settlements that do not meet building codes and are located on steep slopes highly susceptible to landslides. Traditional methods of landslide detection, such as field surveys and aerial photography, can be time-consuming, expensive, and limited by weather conditions. Synthetic Aperture Radar Interferometry (InSAR), on the other hand, can provide frequent and accurate measurements of land surface deformation over large areas, regardless of weather conditions. InSAR can measures ground displacements, with a millimetric precision, allowing to detect and monitor landslide activity over time. The launch of the Copernicus Sentinel-1 satellites in 2014-2016, regularly acquiring SAR data worldwide with a free-data policy, is a potential important source for improving the knowledge of the territory based on this technique. Nevertheless, the use of satellite interferometry (InSAR) techniques is still scarce in Colombia. The aim of this work is to show the InSAR results over the high-density populated city of Medellín, with a focus on the detected slope instabilities representing a potential risk on local infrastructure and communities.

Methods: In this work Sentinel-1 data in both ascending and descending geometries have been processed over the city of Medellín. The derived InSAR displacement maps allowed to detect several areas of ground motion that have been analysed and interpreted with the use of auxiliary spatial data in a Geographic Information System (GIS).

Results: The InSAR-based displacement maps allowed the detection and spatial-temporal characterization of both known and unknown slope movements. Slight displacements of several centimetres have been detected in different sectors of the city. The measured displacement rates are generally less than 1 cm/year. However, although low and possibly imperceptible, these displacements indicate the presence of unstable areas that represent a risk as they could accelerate disastrously. Several areas have been selected to preliminarily assess the relationship between these displacements and the characteristics of the ground and land use.

Conclusions: Overall, SAR interferometry represents a powerful tool for managing risks associated with slope instabilities in mountainous urban settings such as Medellín. The produced InSAR displacement maps can help the Medellin authorities to identify areas at risk and take proactive measures to protect the communities living there. This can include measures such as building retaining walls, reinforcing slopes with vegetation, or relocating residents to safer areas. Moreover, this information can be used to develop early warning systems, to plan and design infrastructure in landslide-prone areas, and to inform emergency response efforts in the event of a landslide.

ACTIVE LANDSLIDES DETECTION USING INTEGRATING REMOTE SENSING TECHNOLOGIES IN THE NORTHWESTERN SICHUAN PROVINCE, CHINA

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Purpose: While China has established a landslide database including about 300,000 active landslides, many recent catastrophic landslides have not been included. Most of them are located on the high-elevation portions of slopes that few people can reach and are densely covered by forests. Thus, traditional investigation methods cannot effectively identify these active landslides, and new investigation technologies are urgently needed to overcome these shortcomings. Since 2000, the Ministry of Natural Resources of China has started to carry out an active landslide identification program in landslide-prone areas of China using multi-source remote sensing technologies. Our team is responsible for the northwestern region of Sichuan Province, including 43 counties (100,000 km^2).

Methods: Firstly, using SAR images (e.g. Sentinel-1, ALOS-2) to detect the deformation area based on Stacking-InSAR, meanwhile, using optical satellite images (e.g. Gaofen-1, Gaofen-2) to manual visual interpret active landslides (identified by morphological characteristics, cracks, etc.) and crosscheck the results of Stacking-InSAR. Then aerial images, airborne LiDAR images and time serials InSAR (e.g., SBAS InSAR) are adopted for detailed investigation in local areas or individual cases. Finally, field investigations for typical active landslides are carried out to check the landslide stability, and to make prevention suggestions (Figure 1).

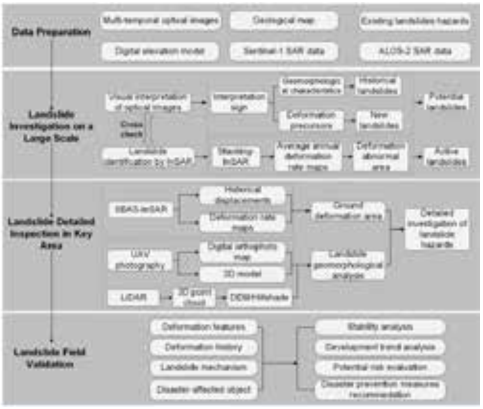

Fig. 1: The workflow adopted in the study for active landslide detection.

Results: 1494 potential active landslides were identified using integrated remote sensing technologies in the study area (Figure 2). We carried out field investigation on 528 of them, and confirmed 393 are real active landslides, with an average identification accuracy of 74.4%.

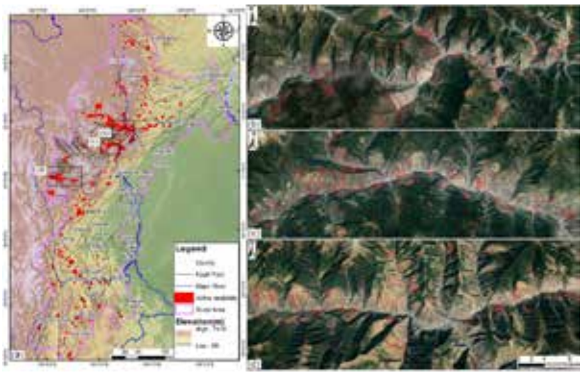

Fig. 2: The distribution of active landslides identified by integrating remote sensing technologies in the study area.

Conclusions: Combining the advantages and limitations of every technology, the integrated spaceborne, airborne, and ground-based collaborative investigation strategy has been proposed to identify active landslides in a broad region. The main findings from this study include:

1. Active landslides often showing obvious macroscopic and microscopic deformation. Macro deformation usually signs can be identified by visual interpretation of optical remote sensing images, while micro deformation can be detected by InSAR technology.
2. Obvious deformation precursors are visible on the sub-meter resolution optical images, such as main cracks at the landslide crown and local collapse on the landslide body.
3. Time series analysis using SAR data allows for the detection and characterization of micro deformation with sub-centimeter precision and accuracy, making it particularly suitable for investigating active landslides. The single-orbit radar satellite image may cause some active landslides to be undetected, while the combined use of the ascending and descending orbit radar satellite images can make the active landslides detected as much as possible.

APPLICATION OF PERSISTENT SCATTERER INTERFEROMETRY CONTINUOUS MONITORING FOR GROUND DISPLACEMENT DETECTION AND CLASSIFICATION IN AN ITALIAN COMPLEX SCENARIO

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Purpose: Persistent Scatterer Interferometry (PSI) is a very useful technique for studying shallow ground displacement (such as slow landslides and subsidence) thanks to its suitability in terms of time intervals and spatial scales covered. Therefore, it can be applied to provide continuous monitoring of ground displacements over regional, national and even continental areas. In this work, we present relevant outcomes of an ongoing four-year (from 2019) collaboration between the University of Florence and the Veneto Region (North eastern Italy) with the aim to improve the knowledge of natural, gravity-induced phenomena and to give scientific support for the management of geohazards. The Veneto Region represents an ideal case of study for testing the suitability of the PSI technique thanks to its complexity in terms of geomorphological features and processes.

Methods: For this work, ESA (European Space Agency) Sentinel-1 satellite constellation, with a revisiting time of 6 and 12 days (until the end of the operative life of Sentinel 1B in January 2022), were implemented. The radar data were automatically analyzed to find displacement anomalies using the time series of each PS (Persistent Scatterer) associated with periods of acceleration and deceleration of the deformation. Finally, the anomalies were classified to recognize the cause of displacement (landslide or subsidence) and to identify relevant anomalies and displacement clusters for further in-depth analyses.

Results: Thanks to the anomaly detection and classification procedures, some relevant cases were identified, especially in Belluno province, being characterized by high anomalous displacement rates within a narrow time interval, such as the Lamosano (anomalous peak displacement rates 98 mm/yr during November 2019-January 2020) and Rivamonte landslides (anomalous peak displacement rates 66 mm/yr during November 2019-January 2020). The anomalies detected were commonly associated with PSs inside known landslides, however, some areas without inventoried landslides but with anomalous displacement trends were detected (e.g. the area of Tiser in the municipality of Gosaldo).

Conclusions: With this work we demonstrate the effectiveness of the use of Sentinel-1 data for continuous and always up-to-date, ground displacement monitoring and how these data can contribute to detect clusters of displacements anomalies with even high displacement rates as well as suggesting updates of landslides in order to give support for risk mitigation strategies.

DETECTION AND MONITORING OF ACTIVE LANDSLIDES AFTER THE INITIAL IMPOUNDMENT OF THE BAIHETAN RESERVOIR (CHINA) USING SAR INTERFEROMETRY

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Purpose: The Baihetan Dam is the second largest hydroelectric power station in China (Figure 1). In April 2021, the reservoir began impounding water, and the water level rose by more than 150 in just 170 days. Therefore, it is crucial to study the impact of the Baihetan reservoir's water impoundment on the slopes on both sides, generate distribution maps of landslides before and after water impoundment, and quantitatively investigate the combined effects of water level changes and rainfall on landslides.

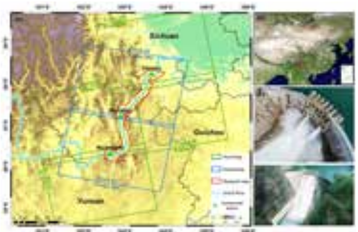

Fig. 1: (a) Location of study area and coverage of SAR images; (b) The location of the study area in China; (c) and (d) Images of the Baihetan Dam.

Fig. 2: Technique flowchart.

Methods: The technique flowchart is shown in Figure 2. Firstly, effective surface deformation was obtained by combining visibility and sensitivity analysis using interferometric synthetic aperture radar (InSAR) technology with Sentinel-1 satellite imagery as the data source. Then, an active landslide distribution map was generated by combining surface deformation, terrain factors, and optical images. Finally, Pearson correlation analysis and wavelet analysis were utilized to quantitatively investigate the correlation between landslide deformation time series and reservoir water level variations and rainfall within the reservoir area.

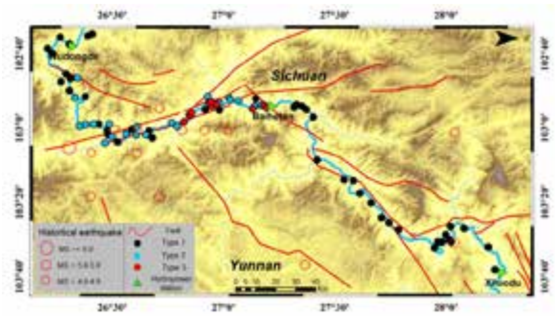

Fig. 3: The inventory map of active landslides in the study area. Type 1 is the landslides that existed both before and after impounding water; Type 2 is the newly developed landslides after impounding water; Type 3 is the landslides that were partially flooded after impounding water. The red lines are the faults, and the red circles indicate historical earthquakes with different magnitudes corresponding to different size.

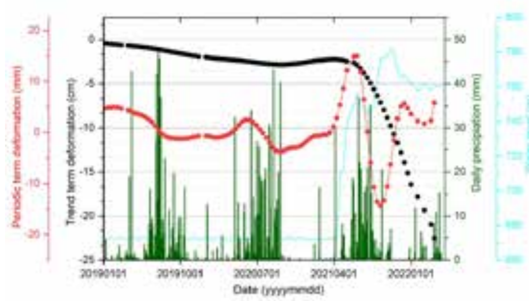

Fig. 4: The correlation between the landslide displacement time series and daily precipitation and water level fluctuations.

Results: A total of 76 active landslides were detected in the study area, where 21 landslides experienced significant deformation after the impoundment of water (Figure 3). One of typical landslide, Mianshawan landslide showed dramatic deformation, specifically the landslide was stable before the impoundment of water, but its deformation rate increased to 15 cm/a after the impoundment (Figure 4). The Pearson correlation between slope displacement and reservoir water level revealed a 72-day lag of the fluctuation of the reservoir water level. Wavelet analysis of landslide deformation and precipitation revealed a 60–90-day time lag. In addition, the first impoundment of the Baihetan reservoir significantly accelerated the displacement of landslide coupling with precipitation.

Conclusions: The impoundment of water in the Baihetan reservoir area had a significant impact on the slopes on both banks, leading to the reaction of 21 landslides. Typical landslide revealed that water level primarily controlled the displacement trend term of the landslide, while both water level variation and precipitation changes influenced the displacement of periodic term.

SESSION 1.4

LANDSLIDES AND SOCIETY: CULTURAL, EDUCATIONAL, ETHICAL, AND SOCIAL ASPECTS IN SUSTAINABLE LANDSLIDE RISK REDUCTION (part I)

PARTICIPATORY, COMMUNITY-LEVEL CO-DESIGN OF A LANDSLIDE WARNING SYSTEM IN RURAL SOUTHEAST ALASKA, USA

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Purpose: Inclusive, participatory governance is a key enabler of effective responses to natural hazard risks exacerbated by climate change. This presentation will describe a community-level co-design process among academic, state, and federal scientists and the community of Sitka to develop a novel landslide warning system for this small coastal town in Southeast Alaska.

Methods: The warning system co-design process engaged with local knowledge and community values and significantly modified the scientists' research agendas and helped navigate sensitivities such as the effect of landslide exposure maps on property values. This case study focuses on our project team's activities and addresses questions including: what activities did the project team conduct, what did these activities intend to accomplish, and did these activities accomplish what they intended?

Results: Formal and informal evaluation suggests that the co-design process generated a warning system the Sitka community finds valuable and shaped the project research to better reflect community interests and values. The decentralized system features an online dashboard which displays current and forecast risk levels to help residents make their own risk management decisions. The system and associated risk communications are informed by new geoscience, social, and information science generated during the course of the project.

Conclusions: Other communities in SE Alaska are now adopting this bottom-up engagement approach. The project concludes with broader implications for the role of community-level, participatory co-design and risk governance for climate services.

LANDSLIDE RECOGNITION IN A MEXICAN MOUNTAIN LOCAL CONTEXT: BUILDING COMMUNITY INTERACTIONS USING UNMANNED AERIAL VEHICLES

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Purpose: This paper aimed to enhance community interactions in a Mexican mountain context to support capacity building to understand landslide hazards and risks.

Methods: The methodology involved a mixed approach, in which community participation perspectives, especially community mapping, were used to share knowledge with people at the local level to recognize the main processes involved in landslide dynamics. In addition, it considered using UAVs to familiarize the population with the aerial view of their territory and the knowledge derived from using UAVs to recognize mountain features associated with landslide hazards. In addition to their knowledge, this approach gave them a broader vision of the interactions between the different elements of the humanized landscape and how the risk of landslide disasters is constructed. A DJI Phantom 4 Pro microdrone was used in collaboration with community members, who were taught the pros and cons of using drones for landslide recognition and assessment.

Results: Insights derived from community mapping and the aerial recognition of landslide dynamics in a Mexican mountain local context by using UAVs allowed the community to improve the understanding of the interactions between the physical and the socio-economic ingredients of landslide disaster risk.

Conclusions: Landslide disaster risk reduction efforts require the sustained participation of local communities. Sharing technological resources, such as using UAVs to recognize landslide dynamics, helped communities better understand landslide hazards and fostered interactions between the science and technology community and society.

EVALUATION OF SOCIAL INTEGRATION DURING THE DEVELOPMENT OF A LANDSLIDE EARLY WARNING SYSTEM IN MEDELLÍN, COLOMBIA

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Since March 2019 the project Inform@Risk has been developing a Participatory Landslide Early Warning System in the barrio of Bello Oriente in the outskirts of the city of Medellín, Colombia. The barrio has suffered from multiple small to medium landslides in the past decades, none of them fatal in part due to the empirical slope monitoring by the local community. Due to the dense population in the lower part of the barrio, community involvement has been a key factor in the project from the very beginning, as presented at the 5th World Landslide Forum in Kyoto in 2021. Naturally, the installation of the sensors for the early warning system caused inconveniences for the community. Some sensors also had to be installed on private property, where permissions had to be obtained from the owners. Thanks to the early and intense approach on community involvement these issues could in general be solved without problems and the monitoring system could be installed successfully in 2022.

During the installation of the different sensors in the barrio, a series of sensor protections that generated new miniature public spaces were developed in order to ensure acceptance of the system among the community and improve daily activities. For example, the main gateway of the sensor system has been built as a community gathering area. It includes a bench, that covers one of the gateways, and a large sign explaining the sensors and their functions. Some singular sensors are covered by small benches and placed at points overlooking the city. The sensors installed at private homes feature a parrot as a part of a series of cartoon characters that help to make the system more appealing and memorable. These integration measures were developed between the Inform@Risk research team, local partners from the academia, government and NGOs and the residents of the barrio. The installation process, which took more than a year, was mostly carried out by members from the community employed by the project through various construction companies.

All these measures aimed at visibility of the project, trust in the early warning system and prevention of vandalization. Several months after the installation none of the installed sensors and other equipment has been vandalized or stolen. This shows the success of the community work in the project by the Colombian partners, the integration of the sensors in the neighbourhood and the inclusion of the community members in the installation process. The project could not have been carried out without any of these aspects of social integration and the further operation of the early warning system, now in the hands of the local authorities, would be next to impossible.

ESTABLISHING HARMONIZED STEPS IN SETTING UP COMMUNITY-BASED EARLY WARNING SYSTEM FOR LANDSLIDES: EXPERIENCES AND PRACTICE FROM THE PHILIPPINES

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Purpose: Increasing the availability and accessibility of early warning systems (EWS) while ensuring the full and meaningful participation of relevant stakeholders are among the targets of the Sendai Framework. Socio-economic impacts of landslides necessitate an EWS for landslides (EWS-L) which has a bottom-up and systematic approach. Hence, EWS-L should be a community-based endeavor. Establishing a community-based EWS-L (CBEWS-L) entails scientific research, technology innovations, socio-technical capacity building, and community engagement approaches and strategies. These are being actualized by Dynaslope, a locally-funded risk reduction project of the Philippine Institute of Volcanology and Seismology (PHIVOLCS) by developing and implementing EWS-L across the Philippines. The Project aims to eventually establish community-based EWS-L in its sites wherein the system is operated and managed by local stakeholders. Sustaining the system at the local level, it is essential to empower the communities at risk of landslides, and local governments to develop, operate, and manage the CBEWS-L. However, gaps in strengthening the capacities of citizen scientists and governments in a CBEWS-L are still present. This study establishes the process of setting-up CBEWS-L that has integrated and systematic processes to have a better chance of fostering collaboration, operationality, institutionalization, and sustainability of the systems.

Methods: This qualitative, exploratory action research employed an action-reflection cycle using people-centered early warning systems, community-based, and citizen science models, frameworks, and principles. Critical constructive analysis of Dynaslope project's practice since 2016 provided insights into establishing the CBEWS-L especially in conceptualizing the processes, methods, and approaches grounded on community engagement and citizen science.

Results: The establishment of CBEWS-L utilizes multi-stakeholder, rights-based and community-based approaches in engaging and mobilizing citizen scientists and local government units of landslide-prone communities. The Dynaslope project proposes harmonized steps in establishing CBEWS-L: 1) site identification and rapport building; 2) training and capacity development; 3) building and consolidating community-based organizations and multi-stakeholder organizational structure; 4) community landslide risk assessment (CLRA); 5) participatory planning; 6) participatory design and development of EWS-L framework and infrastructure and information system; 7) CBEWS-L operations, 8) preparation for the response; 9) institutionalization and mainstreaming; and 10) monitoring, evaluation, accountability, and learning (MEAL). These steps are non-linear and may vary depending on the local context and needs of communities at-risk of landslides. Implementation of strategies and activities of each step considers a people-centered approach, multi-stakeholdership, premiums on the organizational capacities of vulnerable sectors, and sustained capacity development, as essential features of the CBEWS-L.

Conclusions: This experience contributes to the evolving practice of collaborative citizen science, strategies, and principles of empowerment and sustainability to operate, sustain, and institutionalize CBEWS-L.

ASSESSING AND CONTEXTUALIZING SITE-SPECIFIC LANDSLIDE RISK IN THE PHILIPPINES

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Purpose: Risk assessments are conducted to provide information that will be used to draw up strategies that could help reduce the effects of landslides. For effective landslide risk management, strategies should be anchored on understanding the landslide risk components — hazard, exposure, vulnerability, and capacity — that should be appropriately adapted to the context of the at-risk communities. As an attempt to understand and reflect on the unique circumstances of communities in assessing landslide risk, the Dynaslope Project, under the Department of Science and Technology-Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS), conducts community landslide risk assessment (CLRA).

Methods: CLRA is a participatory process of assessing landslide hazards, exposure, vulnerabilities, and capacities of at-risk communities. CLRA includes hazard assessment, participatory community workshops, focus group discussions, and surveys. It was first conducted in three project sites, namely, Pange village in Matnog, Sorsogon Province, and Bacong village in Tulunan, and Kinarum village in Magpet, Cotabato Province. Risk components are assessed, and results are integrated through a semi-quantitative method that utilizes a scoring system with equivalent categorical labels, i.e., low, moderate, and high, to classify each risk component and the overall landslide risk. Priorities of the communities are taken into account in the assessment by letting them identify and validate the elements-at-risk, vulnerability, and capacity indicators, and the corresponding weights that were used in the scoring system. The results are presented in household-level risk maps and landslide risk assessment reports.

Results: Incorporating the weights and indicators of vulnerabilities with the identified exposure and analyzed hazard shows that the three study sites have moderate and high levels of risk in households. The results also reveal that different priorities and outlooks on vulnerabilities were highlighted in the study sites. The community in Kinarum gave importance to disaster risk reduction (DRR) knowledge and awareness as an aspect of vulnerability. In Bacong, on the other hand, vulnerabilities were mainly associated with human aspects. These are reflected in their recommendation for strengthening DRR awareness and conducting activities for the vulnerable sectors. The community in Pange highlighted the importance of natural resources. With natural resources as one of their top priorities, they provided recommendations focused on environmental protection, such as strict enforcement of rules on illegal logging and prevention of backyard burning.

Conclusions: Integrating different risk components with participatory identification of risk indicators shows promising results in drawing out different community contexts that may not be captured solely on a definite set of criteria. This may be useful in developing site-specific risk management strategies and actions. From this, utilization and continuous exploration and improvement of participatory tools and methods of landslide risk assessment are recommended to ensure that at-risk communities can realize and articulate factors that aggravate their risk to landslides hazard.

RAINFALL INDUCED SHALLOW LANDSLIDE HAZARDS PREDICTION (EWS) & MONITORING AT UKHIYA, TEKNAF, COX'S BAZAR, BANGLADESH

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Landslide is one of the major catastrophic disasters in many parts of the world, which usually occurs due to excessive rainfall or earthquakes. It has devastating impacts that can promote numerous deaths, loss of human lives, properties, society & civil infrastructures. Bangladesh is a south Asian Monsoonal Country and the recent change of precipitation pattern in the Cox's Bazar area has an influence to increase the number of monsoonal slope failures and landslide hazards at Ukhiya, Cox's Bazar region. Unfortunately, there is no National Early warning System (EWS) in the investigated area to Predict and monitor landslide hazards to give early warning alert to the community and society. In this research an attempt has been made to evaluate, predicate the shallow landslide hazards at Ukhiya hills, Cox's Bazar, Bangladesh.

More than one million Rohingya refugees who fled from Myanmar, had constructed temporary shelters on the loose unconsolidated sandy hills (SC-SM, SP & ML) of Ukhiya-Teknaf region, Cox's Bazar area, Bangladesh. After entering Bangladesh, the green eco forests of Ukhiya Hills had to be destroyed by cutting trees and hill slopes as they built their shelters which eventually had destructive effects on the ecosystem of Ukhiya Teknaf region. Sands (SP-SM) are mainly uniformly graded and composed of more than 72% to 98 % sand. This research has been carried out to assess the climate variability, rainfall induced slope failures and risks associated with the Ukhiya hills during raining. Recent change of precipitation in the camp area has an strong influence on the hills stability in the Ukhiya refugee camps. Based on factor of safety landslide risk maps are produced for sustainable development in the camp area. Some geo-engineering recommendations are also made to reduce these slope hazards for sustainable community living in the camp area.

This research is also focused to establish a landslide early warning system (EWS) to predict and monitor landslide hazards in the investigated area to fulfill the present research gap. In this research work, we are proposing an innovative landslide prediction and monitoring system that leverages state-of-the-art IoT (Internet of Things) technologies. The microcontroller NodeMCU ESP8266 handles all of these tasks and the system has been programmed using the Arduino code programming language. Special methods and functions are added to the C++ language while writing Arduino code. The stakeholders are notified through SMS and alarm when the system detects excessive rainfall that could result in a landslide. The system can generate (3) types of alert and warnings (viz. Yellow, Orange and Red alerts) to give warnings to the communities and societies to evacuate the site before disasters.

Keywords: Rainfall, Landslide, Threshold, Risk, IoT, Warning, Prediction & Mitigation.

Acknowledgement: This research work is fully supported by ANSO_China (Project Grant: ANSO_CR_PP_2020_08). Thanks to ANSO China.

BUILDING LANDSLIDE RISK CULTURE IN ROMANIA: THE ROLE OF GEOMORPHOLOGY WITHIN A TRANSDISCIPLINARY APPROACH

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Purpose: During the last decade, as concluding from a vast and growing literature, landslides are acknowledged worldwide as representing some the most significant natural risks; their impact on anthropic and natural environments varies in terms of economic, human and environmental damages or losses. Through their complex morphogenesis, and clearly responding to climate variability and change, landslides may potentially interact with similar natural hazards like earthquakes and floods, increasing exponentially, within a multi-hazard risk framework, the level of damages and the potential death toll. It is the purpose of this paper to: (i) outline the sustainability of the risk culture building process, (ii) evaluate the level of adaptive and coping capacities within the local communities, as result of complex socio-cultural and economic features of stakeholders and influencing the risk culture itself, through their values, beliefs, knowledge, attitudes and understanding about or/and face to landslide risk and (iii) provide an overview on how, where and when geomorphic experience is locally valorized by local social capital as a multidimensional resource conditioning and modeling the level of landslide risk culture.

Methods: The geomorphic expertise is completed by the human geographic perspective, these comprehensive approaches assuring not only the knowledge transfer, but also the increase of trust and ability to be connected and to maintain the ties, finally building networks, as a vital factor influencing the development of such a specific risk culture.

Results: In Romania, a country severely affected by landslides induced by hydro-meteorological and seismic triggers, the importance of performing state-of-the-art (multi-) hazard studies at regional and national scales for developing reliable risk estimations, evaluations or management strategies, in support for a proper risk governance, started to be increasingly acknowledged. Following the process of EU joining (2007), Romania started a long and complex process of enhancing its capacities for disaster risk reduction, and landslides were considered among the key risks at a national scale, as outlined by the Romanian National Reports delivered in the framework of HFA and SFDRR.

Conclusions: The development of a risk culture relies on the construction of the most efficient strategies of consequences mitigation, risk management and governance capacity building. The risk culture, regarded as the shared sum of common values, beliefs, knowledge, attitudes and understanding about landslide risk, implies the evaluation, development, implementation and constant revision of proactive and reactive measures, resulting from a transdisciplinary stakeholder engagement. Geomorphology plays a crucial role: the systemic perception of the environment (in general) and of the landslides system (in particular) by the geomorphologists turns them into key stakeholders, whenever addressing space-time predictions of both processes and consequences.

INFORMED DECISIONS FOR EMERGENCY MANAGEMENT TO COPE WITH WEATHER-INDUCED LANDSLIDES: AMALFI TEST CASE

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Purpose: Informed Decisions for Emergency Management (IDEM) is a web Platform, under development, that has the goal of supporting municipal authorities in charge of civil protection, to deal with weather-induced risks. The initiative is being carrying out in the Horizon Europe project “The HuT: The Human-Tech Nexus - Building a Safe Haven to cope with Climate Extremes” (2022-2026, thehut-nexus.eu), which pursues a trans-disciplinary approach overcoming sectoral silos and promoting a full integration between human, governmental and technological factors for effective Disaster Risk Reduction (DRR). The test case is the town of Amalfi (Campania Region, Italy), historically affected by geo-hydrological disasters that induced significant impacts to communities and assets. IDEM is intended to be adopted by the Municipal Operation Centre (Centro Operativo Comunale, COC), the body convened during warning phases associated to potential emergencies for human-induced or natural disasters. The body is chaired by the major and includes the civil protection manager and persons for needed “support functions” (e.g., human health, telecommunications, volunteering, equipment, census of damages, population assistance).

Methods: The Platform is being co-designed and co-developed with members of the Amalfi COC. It is expected to work as a “hub” where different types of information, usually available in different formats and from different sources, are collected and put-to-use of COC members, both during peacetime and during the hectic stages of emergencies.

Results: It includes several functionalities.

- Georeferenced information layers, for instance identified pick-up points, parking areas, recently burnt areas, and temporary scaffolding. The section can be directly populated by COC components or delegates during peace periods.
- Reports about territory vulnerabilities, incipient disasters or past events. The section, following the brilliant example of recent seminal citizen science experiences, is populated by local experts and practitioners acting as “human sentinels”. Indeed, IDEM also allows data submission by local volunteers.
- Real-time weather observations (primarily, precipitation at very high temporal resolution) permitting to monitor the evolution of the potential exceedance of the rainfall thresholds defined by the regional early warning system. The section hosts the observations collected by the official regional civil protection network.
- Complementary information about triggering events and impacts at the ground. In the framework of The HuT project, the official monitoring network is complemented by IoT rain gauges that increase the spatial resolution of the rainfall measurements. Furthermore, soil moisture sensors and streamflow gauges give supplementary information about the potential occurrence of geo-hydrological hazards. The relative low prices of such devices enables an effective and capillary coverage of the considered territory.
- Additional information about the regional warning system and past events affecting the municipality.

Conclusions: IDEM is being developed as both a desktop platform and a mobile app. The latter is intended to be primarily used to collect report from human sentinels and COC members during the emergencies. IDEM provides a brilliant example of The HuT overarching approach to DRR, wherein emergency management (governance) is effectively supported by technology (IoT monitoring, the web Portal itself) and aware human involvement (human sentinels).

SESSION 5.5

ADVANCES IN EARTHQUAKE-INDUCED LANDSLIDE RESEARCH (part I)

SEISMO-TECTONIC IMPACT ON SLOPE PROCESSES IN THE LAKE SEVAN BASIN

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Purpose: Studies of geological hazards and their interactions are of fundamental importance for the Republic of Armenia, which is located on the axial part of Arabia-Eurasian continental collision zone and characterized by a high density of active geological structures. Sevan Lake basin represents 16.4% of the Armenian territory (1240km2 of fresh water), located in a complex geodynamic junction, where there are active geological processes of various origins: tectonic, volcanic, gravitational etc. Therefore, the importance of studying seismotectonic influences on slop processes in the basin of the largest lake in the Caucasus region is significant. The lake is surrounded and crossed by active faults of various kinematics. The northeastern and southwestern limits of the Sevan Lake displays landsliding potential and controlled by Pambak-Sevan-Syunik (PSSF) and Noratus-Kanagegh (NKF) active fault zones. Historical seismicity and paleoseismicity show that the PSSF can produce earthquakes with moment magnitudes Mw>7.0. Accordingly, strong earthquakes in mountainous areas are one of the most important triggering causes of large landslides and collapses.

Methods: The Universal Distinct Element Code 6.0. 337(UDEC 6.0. 337) is a two-dimensional numerical program that simulates the quasi-static or dynamic response to loading of media containing multiple intersecting joint structures. UDEC utilizes an explicit solution scheme that can model complex, nonlinear behaviors.

Results: Thus, a static-dynamic analysis of slope stability was performed in the steepest northwestern part of Lake Sevan as a result of which it is possible to assess the possible development of dangerous slope processes. The factor of safety (FoS) has been determined. Dynamic analysis was carried out. Friuli earthquake (Italy, 1976) with 6.5 magnitude, d=10km, 0.35g was used as a contributory earthquake. The values of acceleration, velocity and displacement of each point of the slope are obtained.

Conclusions: Thus, a complete assessment of slope processes with the latest approaches allows to assess the possible movement of rock masses due to fault features, thus indicating the possibility of such future processes in coastal areas where there is a highway and railway. The factor of stability (FoS) for this slope under static conditions was determined to be 2.33, indicating that the slope is fairly stable under static conditions, 2.33>>1. The parametric analysis, calculated with 10 times weaker parameters of the failure surface, also shows a high value of the slope stability factor, which once again confirms the stability of the slope in the static condition: 1.47>1. The dynamic analysis shows a maximum displacement of about 0.6m and maximum acceleration value of 0.6g. This implies that the slope is partially unstable under dynamic conditions. And, despite the denser distribution of lake-dipping faults (88° SW), the existing opposite direction (42° NE) faults and the PSS fault with its segments (80°NE) seem to act as a counterbalance and balance the significant rock movement towards the lake.

MORPHOMETRY AND HIGH DEPLETION RATE OF LANDSLIDES MAY INDICATE THEIR COSEISMIC ORIGIN

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Purpose: Ancient coseismic landslides might indicate prehistoric earthquakes and could also be a measure of their intensity. Their reliable identification in the landscape remains, however, challenging.

Methods: We analyzed and quantified a variety of morphometric characteristics of the recent large rainfall-triggered and coseismic landslides in different global settings. We focused only on the source areas; the source areas better reflect the effects of the triggering processes on the host rock mass and also these might be better preserved in the topography than the accumulations often subsequently removed by erosion. We analyzed the source-area morphometries of several tens of coseismic and rainfall medium- to deep-seated landslides from different settings, i.e. tropical humid, subtropical arid and temperate zone environments associated with known particular triggers and that revealed clear source area morphology and evidence of an existing shear plane at the base. Landslides from the documented rainfall events in the Czech Republic, Taiwan, Japan, Myanmar, and earthquake triggered landslides from Taiwan, Japan, Haiti, Kyrgyzstan, New Zealand, Costa Rica, Turkey and a couple of published coseismic landslides from other parts the world were included in the study.

Results: In contrast to the rainfall induced landslides, the source areas of coseismic landslides revealed generally relatively higher degree of depletion due to immediate high mass mobility, they occurred in higher slope sectors close to the ridges and edges, and the source-area high depletion occurred at generally relatively gentler slopes than in the case of rainfall landslides. The further quantified and analyzed morphometric parameters comprised the depletion index (Id), i.e. the ratio between the length of the depleted part and the length of the source area, the relative slope height (Hrel) and the source area angle (ϕS), i.e. the angle between the top of the line connecting the scarp top with the toe of the source area and the horizontal plane. We synthetized those parameters into a single number represented by the Index of Potential Dynamic Trigger (IPDT):

$$I\_PDT = (ID+Hrel)/2 - \tan\phi_S$$

that might range hypothetically from -1 to 1.

Generally, the rainfall landslides revealed relatively much lower IPDT values ranging from -0.44 to 0.38 (in case of extreme amount of rainfall due to Typhoon Talas) with an average IPDT 0.00 and median 0.04. On the other hand, the EQ triggered landslides reached much higher positive values ranging from 0.02 to 0.78 with an average IPDT 0.36 and median 0.38.

Conclusions: Although this parameter should be rigorously tested on more comprehensive datasets from other seismic and rainfall landslide events worldwide and with broader context of the casual conditions, we conclude that the Index of Potential Dynamic Trigger can be a useful and simple morphometric tool for the effective preliminary identification of prehistoric earthquake-triggered landslides recorded in the terrain topography. The research was supported by the international Czech-Taiwanese bi-lateral project “Earthquake-triggered landslides in recently-active and stabilized accretionary wedges”, project nr. 22-24206J (GAČR) and 110WFA0710913 (NSTC).

A WEB GIS DATABASE OF THE SCIENTIFIC LITERATURE ON EARTHQUAKE-TRIGGERED LANDSLIDES

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Purpose: Earthquake-triggered landslides (EQTLs) are a widespread phenomenon which frequently occur after significant earthquake events, causing additional damage and casualties. Thus, it is a topic of interest for researchers in the field of geohazards. In this work, we present a web-GIS database containing the most relevant scientific articles on EQTLs. The analyses carried out on the collected material provide general insights which can be useful for experts and general readers.

Methods: To select the main articles published on EQTLs in peer-reviewed international journals, we used the Clarivate analytics' Web of Science-Core CollectionTM online platform. The search allowed to collect articles from 1984 to 2022 that were integrated with other type of information (i.e., ISC Event Bibliography) and verified to confirm the relevance of each article for the topic. After this stage, the articles were systematized into a web-GIS interface that allows the user to search, visualize and analyse different information (e.g., bibliometric information, addressed topics and earthquakes) in a geographic framework. The G3W-SUITE, which is a modular client-server application for the publication and management of QGIS cartographic projects, was used for implementing the web-GIS.

Results: The articles were organized in different categories, considering the addressed topics and sub-topics which, in turn, can be classified based on the scale of the analysis (e.g., regional or single landslide analysis) or the type of the mail research activities (e.g., modelling, mapping, description). The classification allowed to perform preliminary statistics and considerations on the main aspects related to the study of EQTLs. These aspects have been outlined both in general and for specific, relevant earthquake events (e.g., the 2008 Wenchuan earthquake) that, over the years, attracted the attention of the researchers.

Conclusions: The preliminary analyses described in this work highlighted the potential of the web-GIS as a tool for performing cross-correlated searches of articles on EQTLs. In fact, using the geographic component, is possible to restrict the literature search considering one or more specific topics for a given earthquake or study area. Moreover, the simple structure of the database enables the addition of new articles, in order to have an updated product that contain also the most recent seismic events.

MULTI-TEMPORAL INVENTORIES OF EARTHQUAKE-INDUCED LANDSLIDES: DAMAGE EVOLUTION DURING SEISMIC SEQUENCES

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Purpose: High seismicity regions are characterized by the repeated occurrence of earthquakes; each of which may trigger environmental effects, including landslides. Multi-temporal landslide inventories are useful to document the evolution of damage and to identify multiple trigger processes (including non-tectonic factors, such as heavy precipitation) or the recovery through time. In this study, we analyze two crustal seismic sequences that occurred in Indonesia (Lombok) and in the Philippines (Cotabato and Davao del Sur provinces), respectively. The Lombok sequence occurred in July – August 2018 and included four earthquakes with magnitude Mw > 6.0 (up to 6.9). The Cotabato – Davao del Sur seismic sequence comprised four earthquakes as well, with magnitude Mw > 6.0 (max magnitude 6.9), and occurred between October and December 2019.

Methods: We produced multi-temporal landslide inventories from visual interpretation of satellite images (3-m resolution orthorectified Planet images) and mapped landslides as polygons. We analyzed the spatial pattern of landslides by adopting a grid approach and by computing the density and areal percentage on 1 km2 cells. Additionally, we assigned an ESI-07 (Environmental Seismic Intensity) value for each slope movement, using area-volume scaling relations.

Results: For the Lombok sequence, we built two landslide inventories, comprising 4823 and 9319 slope movements, respectively (Ferrario, 2019). For the Cotabato – Davao del Sur sequence, we built three landslide inventories, which include 190 slope movements triggered by the first earthquake of the sequence; 4737 slope movements after earthquakes 2 and 3; and 5666 slope movements at the end of the sequence. The final epicentral ESI-07 intensities were X and IX for Lombok and Cotabato – Davao del Sur sequences, respectively. The landslide inventories for the Lombok sequence are available as a supplementary material in Ferrario (2019), while those referring to the Cotabato – Davao del Sur case history are available in the Zenodo repository at https://doi.org/10.5281/zenodo.7520726.

Conclusions: The availability of satellite imagery with a short revisit time makes it possible to build multi-temporal inventories; these, in turn, allow the documentation of the progression of environmental damage during a seismic sequence. The local geological and geomorphological conditions remained constant over the duration of a few months, such as during the investigated seismic sequences. Nevertheless, the comparison of the two case histories shows that there is a complex interdependency between predisposing and triggering factors, which include seismotectonic factors (e.g., earthquake magnitude, epicentral location) as well as non-tectonic triggers (e.g., rainfall). We claim that the datasets presented in this research are useful both for short-term predictions of landslide susceptibility and for long-term land planning, as well as for evaluating the influence of multiple earthquakes on the geomorphic evolution of an area.

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MAPPING EARTHQUAKE INDUCED LANDSLIDE HAZARD IN ITALY

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Earthquake generated ground shaking triggers widespread environmental coseismic phenomena, defined as secondary Earthquake Environmental Effects in the Environmental Seismic Intensity scale (ESI). Among them, Earthquake Induced Landslides (EILs) are the most diffused, especially affecting young, high relief terrains associated to the ongoing plate tectonic dynamics. EILs can be reactivation of pre-existing landslides or activation of new ones where favourable geologic conditions exist. In this work, we try to answer the following questions: which of the pre-existing landslides more probably will be reactivated, and where is more probable to trigger new EILs during future earthquakes?

We used complementary datasets available for the Italian territory: 1) the Italian and European seismic hazard models showing, over spatially uniform grids, the probability of exceedance of the seismic action within a fixed time span; 2) the Database of Individual Seismogenic Sources (DISS; https://diss.ingv.it/), that includes faults responsible for the seismic activity; 3) the Italian Landslide Inventory database (IFFI); and 4) the European Landslide Susceptibility Map (ELSUS v2). We also used new empirical relationships relating the variation of EILs density with distance from the earthquake epicentre (A), and the variation of EILs density with seismic shaking (B), that were calculated using the Italian database of historical seismic induced landslides (Zei et al., 2023) and a shakemap dataset of historical earthquakes as input data.

To answer the first question, we used the distance corresponding to the 95th percentile of landslide occurrence (95DIST), derived from the empirical relationship (A). This allowed to sum for each landslide the number of possible epicentres located along the DISS composite seismogenic sources and falling within that distance. The location of the epicentres was determined using a floating fault approach, where a typical fault associated to a maximum credible earthquake (MCE), was shifted of a fixed distance along-strike of the seismogenic faults. We also calculated the probability of occurrence of each MCE and derived the probability for each landslide that an earthquake of a certain magnitude could occur within 95DIST.

The second question was addressed merging over a uniform grid the seismic hazard and the landslide susceptibility data, by multiplying their values, and highlighting in this way areas where the probability of triggering new landslides is maximum due to seismic and geologic predisposing factors.

Finally, to obtain the EILs hazard, we calculated the conditional probability of reactivation of each landslide of our dataset. This was obtained combining 1) the cumulated probability of occurrence of the earthquakes of different magnitude classes falling within the 95DIST with 2) the probability of reactivation of the landslide in function of the epicentral distance, as derived from the empirical relationship (A). We also calculated the conditional probability of inducing new landslides using the landslide density function of empirical relationship (B) applied to the seismic hazard and landslide susceptibility combined map.

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SEISMICPY: AN APPLICATION FOR ESTIMATION OF SEISMIC-INDUCED LANDSLIDE HAZARD MAPS

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Purpose: The purpose of the paper is to present a new tool for the analysis of seismic-induced landslide susceptibility zones developed in Python code that allows to minimize the analysis time considerably and to optimize decision making. At the same time, it combines the different current approaches, such as the deterministic model and the probabilistic model, in order to obtain objective results in the event of a seismic event to identify vulnerabilities in terrestrial infrastructures such as roads.

Methods: The study presents a software specifically developed for the preparation of predictive maps of earthquake-induced slope instabilities using the logical tree methodology. The program requires specifying the average geotechnical parameters of the materials present in the region, their variability (10th and 90th percentiles), the size of the instabilities (depth of the failure surface), the location of the water table, the seismic scenario (Peak Ground Acceleration/Arias Intensity and/or magnitude of the event to be analyzed), and up to ten empirical relationships can be selected simultaneously to estimate the Newmark Displacement. The software automatically performs all possible combinations of parameters and evaluates the corresponding predictive maps.

Results: The result is the dissemination of this new software that has been developed, which allows obtaining a multitude of predictive seismic-induced landslide hazard maps, demonstrating its usefulness and applicability with a practical example where a road section in the province of Granada (Spain) is analyzed.

Conclusions: The program allows for obtaining a greater amount of information from different approaches, thereby enabling more objective decision-making for the evaluation of landslide hazards in transportation infrastructures. The viability of incorporating the tool into the analysis and decision-making systems of different international organizations is shown.

POST-EARTHQUAKE CHANGES IN LANDSLIDE HAZARD AND THE ROLE OF DEBRIS CLEARANCE STRATEGIES: A CASE STUDY FROM THE 2016 KAIKŌURA, NZ EARTHQUAKE

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Purpose: Earthquake-induced landslides (EIL) present a chronic post-earthquake hazard, with reactivation and remobilization resulting in ongoing disruption. However, the duration of this ongoing disruption and our ability to hasten the landscape recovery remain contentious. Following the 2016 Mw 7.8 Kaikōura earthquake, >20,000 landslides caused widespread damage to transport infrastructure, isolating communities and severing a nationally significant transport corridor. Intensive debris clearance and slope mitigation works were successful in re-opening the corridor within 13 months of the earthquake, at a cost of >NZ$2 billion. Here, we compare the long-term evolution of EIL along the transport corridor that have undergone substantial mitigation works with the behaviour of 'unmodified' EIL to evaluate the degree to which the emergency mitigation works have influenced the longer-term slope recovery.

Methods: We use a combination of openly accessible Landsat-8 and Sentinel-2 satellite imagery to map landslides annually across the earthquake-affected region between 2013 and 2021. Landslides were mapped as polygons based on visual interpretation using true and false colour imagery. Each epoch was mapped independently with all visible landslides in an epoch mapped. We then compare how both the number and area of landslides across the region have changed throughout the mapping period, as well as explore changes in areal density and landslide shape.

Results: Since the 2016 earthquake, both the number and area of landslides across the entire mapped area have decreased almost linearly but remain 5-6x greater than rates prior to the earthquake. If these decreases continue, landslide rates could return to pre-earthquake levels by ~2025-2026. However, there is a large disparity in recovery across the mapped region. Landslides affecting the transport corridor show far greater decreases in both landslide number (57% decrease) and area (25% decrease) than the nearby Mt Fyffe region, where landslide rates have remained relatively static since the earthquake. This is despite similar initial conditions and post-earthquake rainfall rates. Notably, area-perimeter ratios for EIL in Mt Fyffe have steadily declined since the earthquake, suggesting remobilization of debris, while along the transport corridor area-perimeter ratios have increased. Within the transport corridor itself there are notable disparities, with the northern section experiencing more initial damage than the southern section but also faster decreases in both landslide number and area. Notably, mitigation works in the southern transport corridor primarily focused on protection measures (e.g. rockfall catch fences), while in the northern transport corridor mitigation works focused on a combination of protection, debris removal and slope remediation, including heli-sluicing.

Conclusions: Post-earthquake changes in landslides from the Kaikōura earthquake show that recovery is spatially variable and appears to be significantly faster in regions where mitigation works included debris removal and slope remediation. Locations where mitigation focused on protection measures only show slower declines, while 'unmodified' areas show only marginal decreases. Furthermore, analysis of landslide shape suggests mitigated slopes have experienced lower rates of remobilization than unmitigated slopes. Despite the high $ costs associated with debris removal and slope remediation, the potential to reduce the period of elevated landslide activity may make these costs worthwhile.

EARTHQUAKE ACCELERATED LANDSLIDES: A UNIQUE TYPE OF EARTHQUAKE-INDUCED GEOHAZARD WITH LONG-TERM EFFECTS

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Purpose: Earthquake-induced geohazards often pose a great threat to the safety of human life and property. Among these secondary disasters, earthquake triggered landslides that occur immediately following an earthquake or after a period of time accounts for over 60% of landslide casualties between 2002 and 2010, which is a major concern especially in seismic active regions. This has motivated plentiful studies with a focus on coseismic landslides that collapsed/failed during an earthquake, new post-seismic landslides that were cracked slopes caused by an earthquake and developed into failures by aftershocks or post-seismic rainfalls, and post-seismic reactivations/remobilizations that were coseismic landslide deposits reactivated mostly during rainfall events after earthquakes. However, long-term seismic effects that activated unstable landslides but without causing failures/collapse even after a long period since the earthquake are typically ignored due to the minor, if any, ground changes caused compared to collapsed slopes. These landslides are typically activated with considerably increased displacement rates compared to their pre-earthquake levels (hence referred to as Earthquake Accelerated Landslides, EALs). As a result, they could generate continuous damage to the ground or man-made infrastructure and may develop into catastrophic failures in the future.

Methods & Results: In this study, we used Sentinel-1 radar observations from October 2014 to August 2020 to detect and characterize EALs induced by the 2016-2017 Central Italy earthquake sequence. The EAL detection method we proposed includes four steps: 1) generation of pre- and post-earthquake InSAR velocity fields; 2) location of post-earthquake moving pixels using the Minimum Covariance Determinant (MCD) method; 3) clustering moving pixels into landslide bodies using the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) method; and 4) classification of EALs and non-EALs. Based on this method, we established a large EAL inventory and statistically quantified as a whole their spatial clustering features against a set of landslide conditioning factors. Results show that EALs did not rely on strong seismic shaking or hanging wall effects to occur, and large landslides were more likely to accelerate after earthquakes. We also discovered their accelerating-to-recovering sliding dynamics, and how they differed from the collapsed coseismic landslides. The landslide recovery phenomenon occurred about 3 years after the earthquakes, probably due to the recession of aftershock energy and the closure of earthquake-generated microfractures over time.

Conclusions: Our study serves as an important supplement to the complete picture of the landslide inducing mechanism by earthquakes and contribute to a more comprehensive long-term assessment of landslide risk. We are continuing to focus on this unique type of earthquake-induced geohazard with long-term effects and will create more EAL inventories for earthquakes of different types and magnitudes to better understand the legacy effects of earthquakes.

IMPACT OF EARTHQUAKE-TRIGGERED LANDSLIDES ON ECOSYSTEM ORGANIC CARBON STORAGE

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Purpose: In light of a heightened rate of large earthquakes (M≥ 7.0) since 2010 (Parsons & Geist, 2014), the montane ecosystem is more likely be exposed to the earthquake-induced geohazards. The denudation by coseismic landslides after 2008 Mw 7.9 Wenchuan earthquake introduced a forest biomass loss of 10.9 Tg C, which offset 0.23% of the living biomass carbon stock in Chinese forests (Zeng et al., 2016). Let along the amount of soil organic carbon (OC), as the largest terrestrial carbon pool, being buried and transported. In order to study the impact of earthquake-triggered landslides on ecosystem carbon storage, the ecosystem OC stock distribution are predicted. The ecosystem OC being mobilized and accumulated on landslide deposits after Wenchuan earthquake are quantified. It has shed light on the fate of ecosystem OC induced by a mega earthquake, which could be considered in regional carbon budget or global carbon cycle models.

Methods: The field investigation, laboratory analysis, remote sensing techniques and machine learning based modeling are applied in this study. For field investigation, 59 inactive coseismic landslides and 64 undisturbed sites were selected to measure the tree biomass and soil OC stock based on the modified landslide inventory covering the whole earthquake-affected area. Further details about plot design at field and soil OC calculation can be found in our previous paper (Liu et al., 2022). The biomass equations are applied to estimate the biomass for trees based on the quantitative relationships between tree biomass and dendrometric variables. Besides, in total of 16 environmental covariates related to soil forming and vegetation growing factors are collected to build the prediction model of OC stock prediction.

Results: The total amount of ecosystem OC stock has been decreased from 122.14 $Mg \cdot ha^{-1}$ to 32.38 $Mg \cdot ha^{-1}$, especially the soil OC stock (0-50 cm), which lost 76.6%. The coseismic landslides triggered by Wenchuan earthquake led to a mobilization of 6.127 MgT C, while the ecosystem OC being sequester on landslides area is around 3.742 MgT C through Net Primary Production. Until 2021, the landslide deposit stores around 3.344 MgT C after 13 year recovery, which accounts for the 55% of pre-earthquake level.

Conclusions: The forest has not regenerated to the original community and the ecosystem OC stock has not recovered to pre-earthquake level. Such mega earthquake in montane ecosystem stores a significant amount of carbon through transferring biomass from living to dead respiring pools, while the carbon is sequestered through the vegetation regrowth. The earthquake-induced carbon storage comprises a more important component of the carbon budget and ecosystem services than expected.

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KEY PROBLEMS AND SOLUTIONS ON DEBRIS FLOW CONTROL ENGINEERING AFTER WENCHUAN EARTHQUAKE IN CHINA

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Purpose: Strong earthquakes often induce a substantial rise in secondary geohazards. This problem has been studied more after the Great Kanto Earthquake in Japan and the Chichi Earthquake in Taiwan. In western China, after the 2008 Mw7.9 Wenchuan earthquake, large-scale regional debris flows occurred in 2008, 2009, 2010, 2011, 2013, 2014, and 2019 in the strong earthquake zone. Many control projects have been constructed, including more than 1,000 check dams. Part of the projects were damaged in the subsequent large debris flows. Debris flow after the earthquake is characterized by many loose sources, high frequency and large magnitude. Traditional design parameters and control engineering cannot meet disaster prevention requirements.

Methods: In the 13 years after the Wenchuan earthquake, our research team continued to investigate and study the formation of debris flow in the earthquake area and summarize the reasons for the damage of debris flow control projects. The main research methods used include field surveys, year-by-year observations of damage projects, and numerical simulations of disaster processes.

Results: The study identified the main scientific challenges of post-earthquake debris flow control projects, mainly including underestimation of the loose material source, exceeds estimated peak magnitude, poor anti-abrasion of drainage channel, clogging of drainage holes on check dam, low storage capacity of check dam. These five problems accounted for more than 80% of the reasons for the failure of the control project. In response to the above problems, we have proposed corresponding engineering solutions, including the new blocking structure for loose sources in upstream, the equation for calculating peak magnitude including gully blockage factor, the anti-abrasion technique of discharge guide channel, the improved design of the drainage holes of the check dam, increase in the capacity of the check dam, and an optimal combination of different engineering according to the characteristics of different debris flows.

Conclusions: This optimization concept has been applied in debris flow prevention such as Qipan gully and Shaofang gully in the Wenchuan earthquake area and has achieved good control results. The research provides a reference for subsequent disaster prevention and mitigation in similar earthquake areas.

IMPACT OF COSEISMIC LANDSLIDES ON INFRASTRUCTURE SYSTEMS IN WELLINGTON, NEW ZEALAND

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Purpose: A rupture of the Wellington Fault, which runs through Wellington, NZs capital city, is widely considered to be the greatest seismic risk to NZ. A MW 7.5 earthquake has been posited on the Wellington-Hutt Valley segment of the fault, with an estimated probability of 10-15% occurrence in the next century and potential shaking intensities exceeding MM 10 in Wellington's city centre. Despite coseismic landslides having occurred in previous large earthquakes in this region, the hazard posed in such a scenario has yet to be assessed. This study models coseismic landsliding susceptibility for a MW 7.5 Wellington Fault rupture, estimating plausible runout pathways of potential landslides. Further, this research assesses the extent of built infrastructure situated within predicted runout pathways, to ascertain the potential impacts of coseismic landsliding in this urban environment.

Methods: This research uses a statistical landslide model, applying fuzzy logic within GIS to assess the relationship between ground motion and conditioning factors to determine landslide susceptibility. This empirical model applies conditioning factors of landslides and shaking intensity data to determine fuzzy memberships (landslide susceptibility) across the study area, using a model which differentiates between anthropogenic and unmodified slopes. Outputs of landslide susceptibility modelling have been used to estimate potential runout areas, using viewsheds and reach angles as a proxy, allowing for identification of infrastructure exposed to landslide hazards in this scenario.

Results: Areas of high susceptibility were identified across five districts within the Wellington Region, with plausible estimates of slope failure between 3 and 138 km2. Transport infrastructure situated in high susceptibility areas has a total length of ~40 km, with high exposure predicted for critical routes such as the connection between Wellington City and the Hutt Valley along State Highway 2. Significant infrastructure is located within potential runout pathways of coseismic landslides including SH 2 from Wellington City through the Hutt Valley to Upper Hutt, suburbs to the south and west of Wellington CBD and the hills straddling Hutt Valley across Lower Hutt and Upper Hutt. More than 1500 buildings were found to be situated directly on areas of high susceptibility to slope failure, compared to >100,000 buildings within the highest shaking intensity zone. Neverthless, NZ's stringent building codes suggest many of these buildings should by capable of withstanding even the highest levels of shaking, while few buildings are expected to withstand landslide impacts. Coseismic landslides during a Wellington Fault earthquake therefore present a substantial threat to populations within the high-density urban environment of Wellington City.

Conclusions: The significance of landslides resulting from earthquakes is clear throughout historic seismic events both globally and in Aotearoa-NZ. The fuzzy logic model applied in this research signifies that Wellington City may not be exempt from these impacts, with widespread susceptibility across the Wellington Region. Areas susceptible to slope failure across key transport routes threatens the resilience of people and infrastructure within these areas. Additionally, this scenario may present a globally unprecedented degree of coseismic landsliding within an urban environment, threatening large numbers of buildings and people within Wellington City.

SESSION 6.9

LANDSLIDE STUDIES IN ITALY: STATE OF THE ART AND FUTURE PERSPECTIVES (part I)

TOWARD IMPROVED CHARACTERIZATION OF ROCK SLOPE FAILURE MECHANISMS

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The characterization of rock slopes and landslides has seen major advances over the last decade with the increased application of state-of-the-art multi-sensor remote sensing and sophisticated numerical modelling methods. This paper will present an overview of research on major landslides and rock slope failures with reference to the published literature and to work undertaken as part of collaborative projects between Simon Fraser University, BC, Canada and the Universities of Bologna Ferrara and Urbino, Italy.

Applications of photogrammetry, LiDAR, thermal and hyperspectral imaging will be presented with recommendations for future developments to maximize the benefits of these methods. Remote sensing data at multiple scales, from the outcrop to the mountain slope, will be used to demonstrate the enormous potential these methods provide in addition to the simple measurement of joint data.

The fundamental importance of structural geology and engineering geomorphology in interpreting remote sensing data will be emphasized through major landslides and rock slope case studies. Long-range and UAV remote sensing characterization of rockfall sources zones will be presented and used to suggest varied typical failure rockfall failure modes including shear, gravity fall and extensile dominated modes.

The development of numerical modelling techniques used for simulating rock slope failures and landslides is reviewed focusing on the importance of realistic representation of three-dimensional geological structure and their implication on slope kinematics and damage. Applications of a numerical modelling toolbox for rock slope stability simulation will be presented with an emphasis on selecting the appropriate model based on both the structural geology and rock mass characteristic. The modelling of landslides and rock slopes is shown to be extremely challenging, if not misleading, unless the true kinematics of the "landslide blocks" and their lateral and rear release surfaces is considered.

Data from InSAR, SAR speckle tracking, ground-based RADAR and repeated ground-based LiDAR scanning will show that these techniques have provided step-change increases in our understanding of surface slope deformation. The importance of state-of-the-art slope monitoring is emphasized along with the challenges in its use for constraining numerical models.

Finally, with the availability of large data sets on slope characterization, monitoring and modelling the importance of utilizing mixed and virtual reality 3D- geovisualisation and machine learning methods will be addressed.

COMPLEX MASS MOVEMENTS RELATED TO SECONDARY TOPPLING FAILURE MECHANISMS OF ROCK SLOPES ALONG THE COASTLINE OF APULIA (SOUTH ITALY)

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Purpose: The mechanisms and conditions for particular failure modes observed along coastal cliffs are presented and described. Examples of cliff instability are, in fact, related to complex secondary toppling failures, which occur for natural factors including geological conditions, weathering features and physical-mechanical properties of the materials cropping out on the cliffs (Evans 1981). The work aims to present a kinematic description of these failure modes and the role of the major controlling factors affecting the stability of rocky cliffs, based on two case studies from the San Nicola Island (The Tremiti archipelago) and Sant'Andrea locality (in the surroundings of the town of Melendugno), Apulia (South of Italy).

Methods: Combining on-site investigations, petrophysical and mechanical properties of the materials, based on detailed geological and geotechnical models, potential and actual failure mechanisms of different secondary toppling modes are presented and compared with existing theoretical methods and analytical approaches.

Results: In horizontally-bedded rocky cliffs where massive calcarenite rocks are underlain by predominantly argillaceous rocks, tension-crack toppling along with toppling and slumping failures represent the common failure modes. Differences in mechanical behaviour and weathering state between the materials, together with undercutting and underlying creep or swelling rates, appear to affect the kinematics and mechanisms of the failure modes, closely controlled by primarily joint and tension crack orientations.

Conclusions: Secondary toppling is a complex failure mode in rocky cliffs and may occur in layered sequences where ductile or pseudo-ductile lithofacies are overlain by predominantly brittle lithofacies. The main contributing factors affecting the kinematics of the mass movements appear to have a different weight in different contexts and conditions. Detailed representations of geological and geotechnical models as well as accurate physical and mechanical properties of the materials have to be considered for the correct choice of the method for slope stability analysis, since these are fundamental for slope behaviour prediction and modelling.

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SLOPE STABILITY ANALYSIS OF TERRACED SLOPES ACCOUNTING FOR STATE OF CONSERVATION AND PHYSICAL CHARACTERISTICS OF DRY-STONE WALLS

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Purpose: In recent decades, variations in rainfall regime and progressive abandonment of rural areas have exposed the terraced slopes of the Cinque Terre (Ligurian region, Italy) to accelerated land degradation issues. Dry-stone wall-terrace complex instabilities have driven such an evolving degradation process inducing diffuse damage to properties and settlements, with significant economic implications for the area (Cevasco et al., 2014; Agnoletti et al., 2019). In this scenario, the prospective conservation of the UNESCO cultural landscape of Cinque Terre might be compromised, so that the adoption of mitigation measures in the context of the adaptation to climate change is among the most relevant challenges of the third millennium. However, at present, a comprehensive knowledge of landslides affecting terraces and analytical methods for their prediction to guide mitigation strategy definition is not fully developed, since only a limited number of studies have dealt with this problem (Camera et al., 2014; Brandolini et al., 2018; Preti et al., 2018; Di Napoli et al., 2020). This study aims at contributing to develop this knowledge proposing a specific method of slope stability analysis.

Methods: A slope stability analysis that accounts for physical characteristics of dry-stone walls and state of conservation of terraces, which has been identified by Cevasco et al. (2013) as a major predisposing factor for landslide initiation has been completed using a finite element approach. In the study area two conditions of land use have been identified: cultivated terraces, significantly less prone slope instabilities, and abandoned terraces, consistently more susceptible to landslide initiation. Assuming that cultivated terraces have a better level of maintenance than abandoned terraces, these two scenarios are simulated. In particular, the effects of the conservation state (in terms of soils properties and single rocky elements apposition geometries) are incorporated in a finite element slope stability analysis. Previous studies dealing with this issue considered dry-stone walls as rigid body, neglecting the possible effect of internal discontinuities between forming elements. In this study, the wall is assimilated to a fractured rock mass. Therefore, elements dimension and arrangement are taken into account, and failure potential is estimated considering mechanical properties of the rocky elements interface according to a Mohr-Coulomb failure criterion. Rigid elements are considered as isoelastic materials.

Results: The obtained results indicate the suitability of the proposed procedure for predicting slope stability in a test area of the Cinque Terre (Manarola). Especially, this procedure allow to better identify potential failure surfaces geometry and their change as a consequence of the state of materials forming the terrace (related to the land use) as well as the overall susceptibility to failure also as function of the simulated hydrological conditions.

Conclusions: The method applied provides a useful basis for better deciphering mechanism and conditions of slope failure in terraced landscapes, providing insights into landslide hazard and a basis for identifying areas requiring appropriate risk mitigation strategies.

AGE AND CHARACTERISTICS OF ANOTHER LARGE LANDSLIDE IN THE VAJONT VALLEY - THE PINEDA ROCKLSIDE

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Directly neighbouring the world-famous deposits of the Vajont rockslide disaster from 1963, debris accumulations are outcropped belonging to another massive rock slope failure, known as the Pineda rockslide.

The Pineda rockslide with an original volume of about 125 Mm^3 of predominately Jurassic limestone detached from a dip-slope mountain flank on the opposite valley site of the catastrophic Vajont slide. The failure initiated on a planar to slightly convex rupture surface formed along bedding planes in limestone dipping 25-30 degrees towards the valley. In its initial stages, the rockslide mass moved down along a continuous sliding plane with increasing internal fragmentation. While crashing into the valley floor some alluvial sediments and a trace of lacustrine sediments have been entrained into the now highly fragmented rockslide mass. The deposits also buried a sequence of delta sediments and show some run-up on the opposite bedrock slope. The rockslide accumulations are deeply incised by the Vajont Stream and the Mesazzo Stream that allows an excellent insight in the internal composition and facies distribution.

A large part of the detachment area of the Pineda rockslide shows extraordinary well developed sliding surfaces developed along a lithological contact. We applied 36Cl Surface Exposure Dating on the limestone sliding surfaces which resulted in an event age for the catastrophic Pineda rockslide in the Early Medieval Period of Europe.

A SIMPLE PROCEDURE TO CALIBRATE SOIL PARAMETERS FOR SLOPE STABILITY MODELLING: THE LANGHE (1994) CASE STUDY

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Purpose: Shallow landslides triggered by rainfall represent common geotechnical hazards in Italy. In this context, the hundreds of landslides which occurred in the Piedmont Langhe area in November 1994, still identified among the most extensive areal event in the last 30 years in Italy, are investigated. Exploiting data from the surveys of Campus et al. (1998), here we calibrate simple soil water and mechanical properties (i.e., the saturated permeability and cohesion values) to overcome the large uncertainty affecting the determination of parameters to be used as inputs for physically based soil slip models. This work aims to contribute to the development of reliable soil data inventory that may be of direct interest in slope stability modelling, following Vannocci et al. (2020).

Methods: The analysis was conducted on a small number of cases selected from a sample of 238 observed landslides, to which geometries and geotechnical features were attributed from a regional database. The calibration was performed using a simple hydrological model, i.e. that of Rosso et al. (2006), since it allows a reasonable check on the sensitivity of soil parameter values to the instability conditions. For saturated conductivity, a variation range was obtained, whose upper limit referred to the so-called bucket model. Assuming that part of the rainfall contributes to surface runoff, a lower permeability value was derived using the proportional flow method ψ, consistently with the real dynamics of the processes. Soil cohesion was calibrated by mechanical analysis based on the infinite slope theory, by targeting the Safety Factor SF to assume the value 0.99.

Results: When comparing locally calibrated parameters and the reference ones found in the database some differences arise; in particular, in several cases, based on calibrated values, SFs quite lower than 1 were derived. It must be pointed out that the calibration procedure allowed us to characterize shallow soils, made up of remolded and often vegetated soil, while the regional dataset provide information on undisturbed soil samples, typically collected at depths greater than those of interest.

Conclusions: The possibility of getting reliable soil parameters to be used in physically based modelling of shallow landslides is a complex task. Here we use a calibration method to obtain meaningful saturated hydraulic conductivity and cohesion values, compatible with the observed instabilities. The implications of the differences found between the calibrated parameters and those published in the regional dataset will lay the foundations for subsequent investigations, as this analysis will be part of the research framework of the RETURN Extended Partnership Project.

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KINEMATIC CONTROLLING FACTORS ANALYSIS OF A REACTIVATED AND SLOW MOVING-LANDSLIDE IN THE EASTERN LIGURIA REGION (NORTH-WESTERN ITALY)

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Purpose: Despite their low velocity, reactivated and slow-moving landslides can be source of severe social and economic impacts due to their effects in terms of damage on the built environment. The kinematic behaviour of these slope instabilities can be markedly articulated, involving the alternation of several stages of movement (e.g., acceleration and deceleration phases, rest periods), following both regular and irregular trends over different time scales (e.g., monthly, yearly or seasonal). Among the factors driving their mobility, rainfall and pore-water pressure are the most investigated in literature. However, the relationships between these forcings and displacement mechanisms may not be straightforward. The primary aim of this work is to explore the relationships between rainfall, pore-water pressure and deep displacement in the Fontane landslide, a reactivated and slow-moving mass movement located in the eastern Liguria region (north-western Italy).

Methods: This has been achieved through a detailed analysis of continuous hydro-geotechnical monitoring data series collected for more than two years (i.e., from June 2015 to December 2017). Displacements were measured through four fixed-in-place inclinometric probes while pore-water pressure data were acquired using a pressure transducer. All sensors were positioned at the main deformation zones detected during the previous inclinometric traditional monitoring. First, the main patterns of movement in the selected time interval were examined. Subsequently, the relationships between i) rainfall and landslide kinematics, ii) rainfall and pore-water pressure, iii) landslide displacement and pore-water pressure were analysed. In addition to the previous investigations, electrical resistivity tomography (ERT) surveys allowed to further improve the previous knowledge on the engineering-geological model of the landslide body.

Results: This study revealed that the kinematic of the Fontane landslide follows a typical seasonal trend, showing the alternation of continuous and extremely slow movements and of rest phases into the wet and dry periods, respectively. However, gradual movements can be occasionally interrupted by abrupt accelerations in conjunction with peaks in pore pressure and involving the largest displacements. Conversely, periods of continuous motion do not seem correlated to pore pressure variation. In this regard, monitoring data indicated that the pore pressure response to rainfall is slow and that larger magnitude changes are attained when multi-day periods of abundant rainfall occurred. These findings pointed out that the landslide mobility consists of a complex combination of different mechanisms. Phases of continuous motion were supposed to be correlated to viscous deformations produced by creep-like movement while faster displacements were interpreted as frictional sliding according to a rigid-plastic behaviour driven by pore pressure increase resulting in effective stress reduction. Interestingly, it was found that, during sharp accelerations, the relationship between pore pressure and velocity is non-linear showing hysteresis effect.

Conclusions: The results of this research improve the understanding about past paroxysmic phases of the Fontane landslide, highlighting that the availability of high temporal resolution monitoring data is essential for the in-depth examination of the landslide motion. Furthermore, the obtained outcomes provide very interesting insights into the deformational features and mechanisms of reactivated landslides.

SLOPE STABILITY IN VINEYARDS WITH DIFFERENT SLOPE MANAGEMENT PRACTICES: STATE OF THE ART IN ITALY

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Purpose: Vineyards currently cover ~0.5% of the entire world agricultural areas. A relevant fraction (57%) of the world grape production sustains the billion dollars global wine market and the Italian territory accounts for approximately 10% of the total. In most Italian wine regions, viticulture takes place on steep hilly areas, sometimes terraced, subjected to rainfall-induced shallow landslides. The different agricultural practices adopted to manage the inter rows, like maintenance of bare soil, continued use of heavy machinery for tillage or permanent grass cover, influence soil physical and hydrological features, such as soil density, water content, hydraulic conductivity. The slope management practices have also an important impact on the distribution of grapevine roots in the soil. The density of roots together with their mechanical behavior related to shear and/or tensile forces, increases soil stability and is often used as an effective tool to decrease the occurrence of shallow landslides, which are widespread in different geological contexts characterized by traditional viticulture. The IPL Project WINESLIDES (Slope stability in vineyards with different management practices) has the aim to develop guidelines of slope management practices which can help local communities to develop effective policies and strategies for reducing the risk of shallow landslides in vineyards. The abstract represents the first phase of WINESLIDES project and analyses the effects of agronomic management practices on shallow landslide in vineyards representative of the different geological, geomorphological, and climatic Italian contexts, significant for presence of slope degradation processes, where high-quality wine-producing districts are located (Oltrepò Pavese in Northern Italy, Chianti in Central Italy and Campania in Southern Italy).

Methods: An inventory of the shallow slope stabilities in the studied vineyards was done. The density and the distribution of shallow landslide has been correlated with the slope management techniques.

A geotechnical analysis and hydrological analysis were carried out for the determination of soil physical properties, volumetric characteristics, mechanical properties, water retention curves and permeability. Calcium carbonate, organic matter and pH were also determined. The Soil Saturated hydraulic conductivity (Ks) was measured in field through different devices as a constant head permeameter at different depths. The grapevine root distribution was determined at different distances from the rootstock.

Results and Conclusions The most important parameters involved in shallow landslides in vineyards in the different Italian contexts were assessed. The state of the art allows to identify the slope and soil management practices helping farmers in a specific climatic, geological and geomorphological context to prevent shallow landslide. The work constitutes the starting point for the development of methods for shallow landslide hazard assessment considering the different management practices on vineyards slope.

THE NOVEMBER 26, 2022, DEADLY DEBRIS FLOW AT CASAMICCIOLA TERME (ISCHIA ISLAND, ITALY): INSIGHTS INTO PREDISPOSING, TRIGGERING AND PROPAGATION CONDITIONS

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On November 26, 2022, a very rapid debris flow occurred in Casamicciola Terme (Ischia Island, southern Italy) along the northern slope of Mt. Epomeo (789 m a.s.l.), claiming twelve victims. The landslide involved volcaniclastic soils covering the slope and was triggered after about 5 hours of intense rainfall, with a peak intensity of 43.8 mm/h. The source zone was located close to the mountain top (about 720 m a.s.l.), within a very steep part of the slope and at the base of a rock scarp. The landslide initiated as a debris slide that evolved into a debris avalanche after the debris impacted alterites present along the slope, and, subsequently, it passed to a debris flow entraining most of the soil and vegetation cover along the propagation path, especially along the upper, steep part of the propagation zone, where the flow eroded a deep gully. At about 230 m a.s.l., the debris flow overflowed outside the channel, impacting the surrounding houses. Downslope, mixing with surface runoff, the debris flow evolved to hyperconcentrated flow, which propagated throughout the Casamicciola Terme town down to the coastline.

This event is only the last one of a series of highly catastrophic rainfall-induced debris flows that in the last decades have involved volcaniclastic soil-mantled slopes of Campania.

In this work, results from the analysis of predisposing, triggering factors and propagation modeling are presented, aimed at a better understanding of the process as well as at supporting the assessment of residual hazard. The study was based on field surveys for the recognition of landslide features. In addition, a high-resolution, LIDAR-derived DEM was analyzed, aimed at identifying morphometric characteristics of the landslide and the susceptibility to sliding/erosion/deposition processes of specific slope sectors. Such analyses were carried out using the Slope-Area plots, which allowed the definition of six slope process domains, defined by identifying different threshold values, and the SL.I.DE method. In order to interpret, understand and possibly predict the triggering conditions of potential further landslides in the nearby areas, rainfall data were analyzed and compared with rainfall thresholds already developed for rainfall-induced debris flows of Campania peri-volcanic areas. As a result, the triggering rainfall event was recognized as having a return period greater than 10 years and approaching or exceeding rainfall thresholds. Finally, based on results from field observations and DEM analysis, propagation modeling was carried out through both DAN3D and FLOW-R codes. Models' parameterization was performed by trial-and-error procedure, starting from available literature data. Results from propagation simulations indicate a velocity consistently higher than 10 m/s and a maximum flow thickness of several meters, providing insights in the assessment of residual landslide hazard.

Based on the results regarding triggering and propagation mechanisms, this study is proposed as a reference for future research by providing a framework for the prevention and mitigation of landslide disasters on the Ischia Island.

RETURN PROJECT: GROUND INSTABILITIES - DETECTION, MODELLING AND SCENARIOS

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Purpose: As part of the Extended Partnerships funded by the National Recovery and Resilience Project (PNRR), the RETURN project, started in december 2022, involves a Spoke (VS2) devoted to the reconstruction of multihazard scenarios related to ground instabilities. The objective of this Spoke is to propose an integrated approach for the generation of quantitative scenarios related to landslides, subsidence, sinkholes, liquefaction at scale ranging from local to regional, the latter extendable to a national level. The final aim is to apply these scenarios to infrastructural and urban contexts of socio-economic interest, as well as making them usable in view of a social communication of risk.

Methods: The Spoke involves 125 researchers from 12 of the 26 partners of Return, including Universities (Napoli Federico II, Roma Sapienza, Politecnico di Torino, Padova, Genova, Bologna, Firenze, Bari, Palermo), research institutions (ENEA, OGS) and administrative Institutions (Autorità di Bacino Distrettuale dell'Appennino Meridionale). The research activities foresee a process of analysis based on real scenarios (back analysis), which have constituted case studies for the participating research groups, such as to be considered already the subject of digital/conceptual twins. From these learning cases, rationales will be extrapolated which will be functional to the design of a multihazard forward scenario simulator. Both learning and generation of future scenarios will refer to two natural settings (sub-aerial and submarine) and five types of environments (mountains, hills, plains, coasts, near shore). They will also make use of cataloguing approaches (through inventories and/or geodatabases), monitoring techniques (also through the use of new technologies), numerical modelling, machine- and deep-learning.

Results: The expected result will consist in the generation of multi-hazard scenarios of effects connected to ground instabilities applied to a proof of concept that will not be site-specific but topologically versatile, which will allow to be extrapolated in its future applications to specific contexts represented on the national territory. Of specific interest for the results of the project is the possibility of triggering the aforementioned scenarios through impulsive stressors (e.g., earthquakes, intense rainfall) taking into account the preparation for instability induced by processes acting in the medium-long term (such as weathering, debris covering, debris fragmentation) which are effective on environmental contexts predisposed by their specific geological and geomorphological asset.

Conclusions: This project is a challenge as it aims at upgrading, in the panorama of geological risk mitigation strategies, the analysis of ground instabilities processes. From the point of view of social resilience, sizing preventive or mitigating strategies on the basis of scenarios that prefigure the distribution of ground instabilities, can significantly raise their reliability and feasibility. From the point of view of social resilience, there is no doubt that being able to size preventive or mitigating strategies, on the basis of scenarios that prefigure the distribution of instability, increases the reliability and feasibility of these strategies. This is just in line with the objective of the PNRR and with the prospects for a rising resilience of the new generations.

SESSION 4.9

LAND USE AND SLOPE MANAGEMENT PRACTICES WITH LANDSLIDE OCCURRENCE: PAST, RECENT AND FUTURE CHALLENGES AND ADAPTATION STRATEGIES

RHETICUS DISPLACEMENT TO SUPPORT THE DESIGN, CONSTRUCTION, AND MAINTENAINCE OF INFRASTRUCTURES AND CONSOLIDATION WORKS

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Purpose: In 2021, the Special Commissioner for mitigating the hydrogeological risk of the Apulia Region has identified 16 engineering companies for the assignment of engineering and architectural technical services for the reduction of hydrogeological risk (Landslide Plan). The projects were related to 16 lots, located mainly in the Daunia area (north of Apulia Region), for interventions financed through the Operational Plan FSC Environment 2014-2020.

Methods: To support the planning and construction of the consolidation works, the Special Commissioner has planned an in-depth monitoring of the evolutionary kinematics of the instability. In particular, support for the design activities with updated information related to the historical ground motion movements has been foreseen for each scheduled mitigation intervention. In particular, in addition to the in-situ monitoring systems (existing or planned), the integration of the satellite monitoring through the multi-temporal interferometry technique was requested to monitor the areas objects of the stabilization works. The Multi-Temporal Interferometry provides a synoptic picture of the monitored phenomena of instability that is useful to support the design activities, and the Special Commissioner's activities.

Results: To answer these needs, the Rheticus Displacement satellite monitoring service provided by Planetek Italia was adopted for the monitoring of the areas subject to interventions. This service provided the ground motion measurements over the areas of intervention subject to instability phenomenon through the processing of data acquired both from Sentinel-1 and COSMO-SkyMed radar satellite constellations processed with the interferometric technique based on the SPINUA algorithm. The Rheticus Displacement service provided the ground motion maps and the historical time series of displacement and geo-analytics for each Persistent Scatterers (PS) and Distributed Scatterers (DS) over the time interval 2015 – 2020. The geo-analytics information has been made available to the Special Commissioner's Office technicians and the designers through the Rheticus Displacement cloud platform. In addition to the Rheticus Displacement access, Planetek Italia provided dedicated on-the-job training to the technicians in charge of the design activities focusing on the results produced with the interferometric analysis and on the functionality of the Rheticus geo-portal. The training activities were essential for fully exploiting the results and their integration within the design phase of the intervention works.

Conclusions: Currently, the Rheticus Displacement service is adopted by the Special Commissioner of Apulia Region, among the actions, to monitor the impact of the realized mitigation works continuously, guaranteeing optimal maintenance of the territory over the areas of interest.

HISTORICAL LANDSLIDE ACTIVITY AND LAND ABANDONMENT IN A CHANGING CLIMATE: ASSESSING THE ROLE OF TEMPORAL RESOLUTION

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Purpose: Mountain drainage basins of the Northern Apennines, and in particular those underlain by claystones of the Allochthonous Ligurian Complex, are dominated by intense landslide activity operated by earth slides and flows, and by widespread badland erosion. Today, a long history of deforestation and land cover changes has generated a landscape with sparse, coppice managed, forest cover. In these settings, quantitative knowledge on landslide occurrence in relation to inherited and ongoing land cover changes is limited, hence preventing suitable strategies of land management. To address this gap, we conduct a multi-temporal inventory in clay-dominated terrain of the Sillaro River basin (139 km^2) in relation to historical land cover changes and concurrent meteorological forcing.

Methods: Historical landslide activity, here investigated through visual inspection of 12 sequential aerial photo sets (i.e., 1954, 1969, 1976, 1988, 1996, 2000, 2006, 2008, 2011, 2014, 2016, and 2018) and complementary fieldwork, is quantified in terms of landslide density. Landslides are characterized according to movement type (earth slide, flow and complex), temporal nature (episodic vs recurring), as well as lithology (claystones of the Ligurian (L claystones), Epiligurian (E claystones), and Padano-Adriatic (P-A claystones) Units, sandstones & marls of the terrigenous Flysch Complex) and land cover (arable crops and meadows, transitional shrubland, managed forest, and badlands) at initiation. Land cover change is evaluated across four periods: pre 1954, 1955-1976, 1977-1996, and 1997-2018. Concurrently, to account for the historical variability of meteorological forcing, three precipitation indices: (i) the annual total precipitation (PRCPTOT); (ii) the annual maximum daily precipitation (RX1day); and (iii) the precipitation fraction (R99pTOT) due to extremely wet days.

Results: We mapped 1164 landslides, for a combined area of about 4.4 km2 (i.e., initiation and transportation zones). At single landslide sites, number of recurrences ranges from 1 to 9. Landslide activity is highest in claystones and landsliding appears strongly controlled by lithology. In particular, we find that in claystone-dominated terrain, landslides density is highest in badlands across all four time periods examined, followed by transitional shrubland, managed forest, and arable crops. Conversely, in sandstones & marls landslide density is highest in managed forest, followed by shrubland and arable crops. Overall, landslide activity is highest between 1997 and 2018, during a period of land-cover stability, where a decrease in total precipitation and a relative increase of extreme events is recorded. However, this finding appears to be biased by the varying temporal resolution of the inventory: photosets are 7-to-15 years apart before 1996, and 2-to-6 years after 1996. Indeed, a visibility test conducted on 68 post-2000 landslides, shows that after 10 years, complete visibility - hence our ability to delineate polygon outlines reliably - becomes rare (6%), and that an additional 11% of landslides remain partly visible, indirectly pointing at a reduction in inventory completeness before 1996.

Conclusions: Badlands are by far the most unstable areas and the most sensitive sites to changes in meteorological forcing within the landscape. Land cover and climatic effects on landslide activity need to be considered in relation to landslide visibility (i.e., persistence) through time.

EVALUATING THE ROLE OF LAND COVER AND ITS CHANGES IN THE INITIATION OF RAINFALL-INDUCED SHALLOW LANDSLIDES IN ITALY

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Purpose: Land use and land cover, and their changes, influence landslide occurrence. They act as landslide predisposing factors and affect the distribution of the vulnerable elements; therefore, they influence both landslide hazard and risk. Evaluating the role of land cover, and its change, in the initiation of rainfall-induced landslides is useful for landslide risk analysis and management.

Methods: In this work, we used the recently published catalogue of rainfall-induced landslides occurred in Italy (ITALICA, [1]), which lists 6312 records with information on rainfall-induced landslides that occurred over the Italian territory between January 1996 and December 2021, with high spatial and temporal accuracy. Moreover, we used four releases of the Corine Land Cover (CLC) maps [2], namely CLC2000, CLC2006, CLC2012, and CLC2018. We associated a land cover class to each landslide in the catalogue according to its spatial and temporal features. As an example, all landslides occurred between 2016 and 2021 were associated to the CLC2018 map. We evaluated the number and density of landslides in each class and their spatial and temporal changes during the years. We investigated also if the spatial and temporal distributions of the landslides (e.g. annual and monthly distribution) changed in different land cover classes. Taking the Marche region (central Italy) as a hot spot (having this region 1220 records in the national catalogue), we analyzed if the rainfall triggering conditions of the landslides changed in the different land cover classes.

Results: We observed that around half of the landslides in the Italian catalogue occurred in agricultural areas. However, in the recent-most years, the percentage of landslides occurred in both urbanized and forested areas increased considerably. The monthly distribution of landslides is different: in agricultural areas the landslides are homogenously distributed in DJF, MAM, and SON; in forested and semi-natural areas more than half of the evens occurred in JJA and SON. Regarding the Marche region, two thirds of the landslides occurred in agricultural areas. The landslide triggering conditions are different: overall, less rain is needed to trigger a landslide in agricultural areas then in forested and semi-natural areas.

Conclusions: We observed spatial and temporal changes in the distribution of landslides in the Corine land cover classes in Italy, and in the landslide triggering conditions. These preliminary findings can be used future evaluation of changes in landslide initiation in response to projected land cover changes.

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EVALUATION OF THE POTENTIAL BENEFITS OF TAKING INTO ACCOUNT VINEYARD INTER-ROW MANAGEMENT IN LANDSLIDE SUSCEPTIBILITY MODELLING

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Purpose: Rainfall-induced shallow landslides can cause significant damage to agricultural practices, by mobilizing the uppermost soil layer (< 2 m), following intense rainfall events. Viticulture is particularly vulnerable to the impact of shallow landslides, due to vineyards being commonly grown on hillslopes. Physically based and probabilistic modelling is often adopted to predict which areas are susceptible to the formation of shallow landslides, most commonly grouping all vineyards within the same land use category. However, not all vineyards are alike: commonly employed management techniques for inter-row management include (1) Permanent Grass Cover (PGC - grass grows between vineyard rows); (2) ALTernating tillage-grass (ALT – tillage of every other row) and (3) Tillage and Total Tillage (T/TT - tillage of all inter-rows). Field testing revealed how root cohesion can vary significantly between different land use practices, from a minimum of 0.34 kPa for T and TT to a maximum of 14.07 kPa for ALT vineyards. This work was carried out as part of the IPL 2020 WINESLIDES, LIFE-DRIVE and VIRECLI projects. It aims to evaluate if taking into account the vineyard management practice would be beneficial in a modelling setting.

Methods: The model chosen to test the hypothesis is a probabilistic version of the physically based landscape evolution model LAPSUS-LS, which simulates soil movement by calculating the critical rainfall needed to trigger a landslide. It requires inputs for geotechnical and land-use-related parameters (such as root cohesion) from a range of acceptable values. The model was applied to the test site of Rio Vergomberra (Canneto Pavese, PV), a 0.54 km2 catchment, characterized by silty soils, located in the Oltrepò Pavese (Italy), where all mentioned management techniques are adopted.

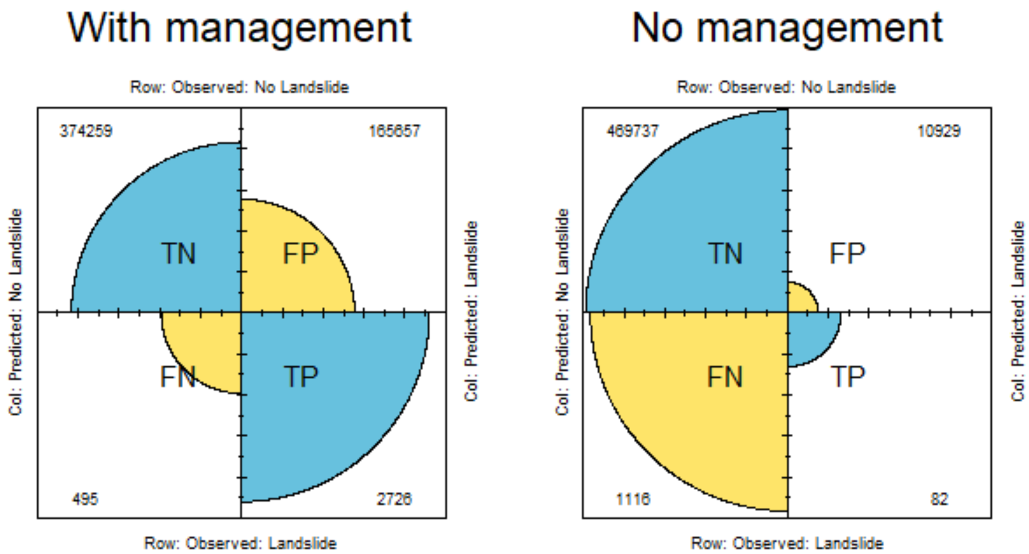

Fig. 1: Fourfold plot of the results.

Results: A fourfold plot is presented in Figure 1: the plot on the left was obtained by taking into account vineyard management, whereas the one on the right was obtained using root cohesion values taken at random from a range of plausible values.

Conclusions: While possibly time consuming to gather such information for modelling, including vineyard management specific inputs proved to be highly beneficial. Including vineyard management practises significantly increased the number of correctly identified unstable pixels (TP value) and lowered the number of unstable cells which were missed by the model (FN value).

LANDSLIDE HAZARDS ON THE FRAGILE VOLCANIC MOUNTAIN ELGON IN EASTERN UGANDA. DO THE SPATIAL PATTERNS SIGNIFY A SUSTAINABILITY PARADOX OR MALADAPTATION?

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Purpose: The fragile mountain Elgon has experienced and increased occurrence of landslide hazards over the last 10 years. A prevailing thesis to the increasing occurrence of landslides anecdotally implicates climate change as the overwhelming factor underpinning increasing incidences. The thrust of this study was to investigate the spatial and temporal patterns of landslide hazards on mountain, with keen interest on attribution of the increasing incidences. We interrogated as to whether well intentioned implemented land conservation and crop yield enhancement measures are inducing unintended alterations in slope integrity on mountain Elgon.

Methods: We compiled an inventory of georeferenced data on landslide hazards with a temporal dimension through a field campaign coupled with collation from secondary sources. The data was entered in an Arcmap GIS environment and combined with other secondary data notably, Digital Elevation Model (DEM), geology, soils, land use and rainfall to spatial analysis. We field-measured the proximity of landslide scars to linear features as well as insitu soil and water conservation measures. In addition, we conducted interviews to elicit information on land use and perceptions of the land users.

Results: The results show the occurrence of both surficial and deep-seated landslides with on mountain Elgon with the former and latter more prevalent at altitudes of <1500 and >1500masl respectively. The highest landslide hazards (70%) occurred in elevation segment between 1500 and 1900 meters above sea level. The predominant hillslopes registering landslide (69%) have slope gradient between 20 to 60%. The size of landslide scars varies but measure expansively up to 101,102m2 and are predominant on sites under agricultural intercropped land uses. Spatial autocorrelation based on Moran's I was observed in the landslide scars depicting concentric and densified concentrations. A temporal analysis shows a shift of landslide occurrence to higher altitudes The results premised on geospatial modelling of 278 landslide scars reveals hotspot geologically and pedologically underlain to biotite granite and Lixic ferralsol soils respectively. Land use has two discernible impacts on landslide patterns on mountain Elgon; (1) transformations and conversions from natural cover to annual cropping is recently brining in new areas under severe and high magnitude landslides albeit with high crop productivity, prevalently at higher elevations (2) implementation of soil and water conservation measures aimed at arresting land degradation and propelling higher yields have on the contrary concentrated soil water infiltration at specific location culminating into slope failures in mid segment altitudes of mountain Elgon. Steady state soil water infiltration rates on mountain Elgon are known to be highly heterogenous varying from 1.2 cm h−1 to 363.0 cm h−1, significantly controlling landslide patterns. Landslide scars in the lower altitude segments were found to be in a distance of about 10 meters to either a footpath linear feature or a soil and water conservation measure.

Conclusions: Our analysis reveal that the geology and land use are the most significant controls of the landslide patterns on mountain Elgon. While implemented soil and water conservation measures are sound for nutrient management in the soils, they have adverse slope integrity implications and require revisitation.

SIMPLE METHOD OF RISK ASSESSMENT FOR LANDSLIDES: A CASE STUDY OF THE JICA PROJECT IN HONDURAS

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Purpose: This study shows how not only landslide experts but also people involved in landslide countermeasures can perform risk assessment from risk map creation. It also aims to explore flexible survey methods so that the methods developed in the target area can be applied to other areas. Honduras was affected by Hurricane Mitch, which struck Central America, including neighboring countries, from October 22, 1998 to November 5, 1998. In Tegucigalpa in particular, landslides and floods caused enormous damage, including many deaths. Against this background, we have tried and errored to find a risk assessment method that is as quick and simple as possible.

Methods: Figure 1 shows the flow from hazard map creation to risk assessment. Field survey sheets and GIS are mainly used here, and indoor work and outdoor activities are regarded as one set of work. This means that even in a short period of time, for example, 2-3 days, it is possible to master the technique by repeating it. Risk assessment work using GIS maps is performed in the following procedure.
1. GIS work in the pilot area according to the work procedure for the impact area of the landslide.
2. Conduct a survey of the number of public facilities and general buildings within the impact area.
3. Implement evaluation results based on the risk evaluation matrix and register the results in GIS.
4. GIS work on overlaying high-risk layers above lower-risk layers.

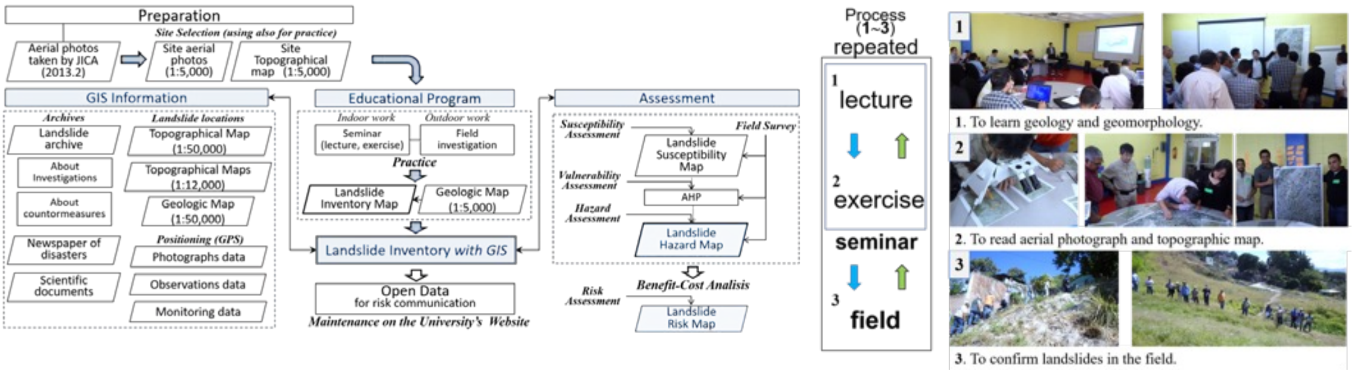

Fig. 1: Flow of landslide hazard mapping system including educational program and assessment, left: flow, right: educational procedure (modified from Hirota, et at. 2017).

Results: Based on the existing landslide distribution maps and newly surveyed data, the extended landslide distribution map and field surveys using them were used to conduct risk assessments and create the landslide risk map. The following items were prepared for thinking of the risk assessment.
1. Geologic map covered the landslide area
2. Landslide inventory map
3. Relief energy and Slope inclination map by GIS
4. Survey sheets for the investigation of landslides
5. Landslide vulnerability map
6. Landslide hazard map
7. Matrix Diagram of judgment for landslide risk assessment
8. Landslide risk map
9. Diagram of action range and relationship of disaster prevention actors (concept)

Conclusions: These studies are ongoing and will enable non-specialists to understand and assess the risks of landslides. The landslide risk map is also useful for ensuring the coordination of self-help, mutual help, and public help when evacuating. In the future, we would like to complete an assessment program based on survey sheets so that we can assess landslide risks in other areas using the methods we are currently using.

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QUANTITATIVE RISK ANALYSIS AND MITIGATION SELECTION STRATEGY OF LANDSLIDE-TRIGGERED HAZARD CHAIN IN RESERVOIR AREA: A CASE STUDY OF LANDSLIDE RISK MANAGEMENT PRACTICES IN THE THREE GORGES RESERVOIR AREA

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Purpose: Hazard chains triggered by landslides, involving the landslide itself as well as potential tsunamis, pose a serious threat in reservoir area. Previous studies have proposed quantitative methods for evaluating landslide risk and targeted strategies for mitigating landslide occurrence. However, quantifying the risk of landslide-triggered tsunamis or the impact of mitigation measures on controlling secondary risks to effectively manage hazard chains remains a significant challenge. In this study, an improved framework, including hazard and risk identification, hazard analysis, consequence analysis, risk estimation, risk decision, risk control, monitoring and feedback, is proposed for risk management of a landslide-triggered hazard chain, through a case study of the Liangshuijing landslide management practices in the Three Gorges Reservoir area, China.

Methods: The hazards of the landslide and its triggered tsunamis were expressed as their respective probabilities of occurrence and were predicted through calculations of landslide stability, run-out analysis and simulations of tsunami propagation. The elements at risk were classified according to their types, relative position with respect to the hazards, and whether static or dynamic. Their vulnerability was quantified based on their resistance to the hazard and the hazard intensity. The total risk was estimated as the sum of direct risk from the landslide and indirect risk from potential tsunamis. To capture the complexity of dynamic risk, risk maps were developed to showcase the distribution and magnitude throughout the hazard chain. Then, risk decisions, such as retention, reduction, avoidance, transfer etc., were made based on risk prediction results and the local economic level. Risk control plan was selected based on a cost-benefit analysis that involved a risk re-assessment to determine the residual risk. Additionally, the long-term effectiveness and adverse effects of mitigation measures were considered by introducing time-effect parameters such as implementation period, service period, and environmental recovery period. Finally, the real-time changes in the hazard chain risks were tracked continuously through monitoring, inspections, etc., in order to promptly update and adjust risk decision-making and mitigation plans.

Results: Through a retrospective analysis of risk management practices for the Liangshuijing landslide, our results shed light on the relative magnitude and distribution characteristics of the direct and indirect risks, the impact of reservoir water level fluctuation on risk results, and the cost-benefit characteristics of mitigation measures that fully or partially control risks. Cutting and drainage engineering may be the best risk control plan for large landslides that could trigger tsunamis.

Conclusions: Our findings provide new insight into mitigation strategy and risk management of landslides in the vicinity of reservoirs: given that indirect risk may be much greater than direct risk, it is essential to emphasize the risk assessment and mitigation strategy of potential secondary tsunamis. For decision-makers, a zero-risk strategy may not always be the optimal plan for hazard chains, but rather a cost-effective plan that focus on controlling the major risks typically tsunami risks caused by landslides uninhabited.

COMMUNITY INTERVENTION IN LANDSLIDE SCAR USE IN THE UPPER MANAFWA CATCHMENT IN EASTERN UGANDA

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Purpose: The risk of landslides is increasing on the slopes of Mt Elgon in the upper Manafwa catchment in Eastern Uganda; landslides have affected the landscape and people's livelihoods. A study to analyse the utilization of landslide landscapes within the upper Manafwa watershed was undertaken. The study aimed at establishing and evaluating landslide characteristics for effective utilization of landslide landscapes in the watershed.

Methods: Field investigations were conducted to characterize landslide scars and their distribution. Household and key informant interviews as well as focus group discussions were held to establish community interventions and their effectiveness in the rehabilitation and use of landslide scars which were rated on a five-point scale

Results: Positive and negative linear relationships were determined between different adoption factors alongside the local interventions. Afforestation and mixed cropping were the most popular responses. Runoff channels and application of fertilisers were the least popular interventions. Grass strips, runoff channels and mixed cropping were perceived as the most effective community interventions.

Conclusions: Local communities have adopted various interventions to rehabilitate the landslide scars. Although afforestation and agroforestry are the most dominant, they are the least effective local intervention measures in the restoration of landslide landscapes. Afforestation and agroforestry should be encouraged especially for areas experiencing shallow landslides since they have been found to be effective against their effects.

FATAL LANDSLIDES DURING THE JANUARY AND FEBRUARY 2023 RAINSTORMS IN AUCKLAND, NEW ZEALAND: SLOPE, LEGISLATION AND INSURANCE FAILURE

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Purpose: Much of Auckland on New Zealand's North Island, is at moderate to high landslide risk, especially during rainfall. Often, houses are built close to cliff edges, with minimal setback, or close to the foot of active slopes, and can be inundated by landslides. The January and February 2023 rainfall events caused widespread landslides (and flooding), multiple fatalities, tens of billions of dollars of damage, with a national state of emergency declared. In particular, two fatal rainfall-triggered landslides occurred in Auckland (at Parnell and Muriwai). We report these two landslide events, site construction history, and describe the legislative and societal context that fails to discourage house-building close to unstable slopes.

Methods: The geomorphology of Parnell (27 January 2023) and Muriwai (13 February 2023) landslides was investigated via site visits and remote sensing, including LiDAR and satellite imagery (SPOT, Pléiades-Neo). Historical aerial imagery provided a house construction and land development time-series. Meteorological data was provided by the National Institute of Water and Atmospheric Research (NIWA). The legislative history, including establishment of the Natural Hazards Commission (formerly the Earthquake Commission) is gleaned from primary and secondary legislation, Parliamentary debates and relevant case law. It provides context to the development of the two chosen landslide sites.

Results: Both fatal landslides occurred following high-intensity rainstorms on slope materials exhibiting high antecedent moisture contents. Parnell landslide occurred in weathered Miocene-age 'East Coast Bays Formation' rock and residual soil during rainfall (150 mm/4 hours), with landslide debris inundating a house below. Muriwai landsliding occurred during rainfall (~250 mm/24 hours) from Cyclone Gabrielle, in weak Plio-Pleistocene 'Kaihu Sands', killing two firefighters. Both Parnell and Muriwai landslides occurred very close to houses destroyed in prior fatal landslides in earlier decades, with houses subsequently rebuilt. House-building on unstable land is a legacy issue in New Zealand facilitated by two legalities. First, a public compensation scheme exists for many natural hazards. This creates a moral hazard by reducing incentives to guard against risk, as few reciprocal precautionary obligations are demanded. This hazard continues (McAneney et al., 2016). Second, local planning legislation allowed councils to approve relocatable building on unstable land, and be absolved of civil liability, without due attention to the potential speed of ground failure. Although these buildings were excluded from state compensation, there was little publicity given to their vulnerability. Additionally, at the landslides studied here, adequate 'setback' distances were not applied, increasing the risk of loss of life and property damage.

Conclusions: New Zealand is fortunate to have the Natural Hazards Commission as it, and its previous incarnations, have cushioned citizens against a variety of natural disasters for >70 years. While 8000 'at imminent risk' houses were purchased by the government following the Canterbury Earthquakes (2010-11), the level of protection that the country can afford in future will be limited, despite the participation of the local insurance market and the international re-insurance market.

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CONCEPTUAL FRAMEWORK FOR SAFETY AND SUSTAINABILITY OF BUILDINGS EXPOSED TO LANDSLIDES IN HILLY TERRAINS OF INDIA

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Purpose: The fragile landscape of hilly regions of India is susceptible to several disasters like earthquakes, landslides, snow avalanche and flash floods. The highly sensitive hilly regions have also been subjected to enormous amount of pressure, primarily due to the escalating population thereby leading to overexploitation of natural resources. Thus, the amalgamation of ecological disruption either due to natural or anthropogenic activities is making the buildings unsafe. Researchers and scientists working in this domain have conducted several studies and devised numerous technological interventions to reduce the impact of such hazard on buildings and make it safe for the community. Nevertheless, unplanned & uncontrolled construction activities, overseeing of building bylaws, using inappropriate building materials, poor workmanship, constructing buildings in the vulnerable zones and unawareness of the local community are some of the most common challenges in making the buildings safe and sustainable (with reference to landslide disaster). Since building represents safety and security of the residents along with their emotional attachment after investing all their hard-earned money, it acts as the backbone of human-coping capacity. But when the buildings are vulnerable to disasters like landslide, it needs to be addressed on priority basis, in order to avert adverse situations.

Methods: Keeping in view the above context, this study intends to present a step wise conceptual framework that enlightens the four key components in order to achieve safe & sustainable buildings exposed to landslides in the hilly terrains of India. The first component will discuss about the importance of vulnerability and risk assessment of buildings. The second component includes development, integration & dissemination (DID) of landslide monitoring and early warning system. The third component aims to provide local intervention at district, block and - local government (city corporation, municipalities and panchayaths) level for the mitigation of landslide. The fourth component will focus on the need of community awareness and capacity buildings in the landslide prone region.

Results: The proposed conceptual framework will provide a way forward towards making the landslide exposed building safe and sustainable not only for Indian scenarios but also for other developing countries. This study will discuss about Joshimath landslide-subsidence incident (aggravated in the month of January 2023). This incident led to the development of cracks in over 800 buildings and immediate evacuation & rehabilitation of more than 250 families. This study will emphasize how the development of such framework, will contribute to avert grave situations as seen in case of Joshimath township.

Conclusions: The intended study will discuss the way forward by elaborating efficient strategies and measures to ensure safety and sustainability of the buildings exposed to landslides in the hilly terrain. This framework will also enable the stakeholders, practitioners, decision-makers and policymakers to take reliable, accurate, understandable and timely actions to safeguard people, their assets and livelihoods.

PRELIMINARY RESULTS OF ANIONIC POLYACRYLAMIDE APPLICATION ON RECONSTITUTED SOILS FOR ANALYSIS OF PROPERTIES INFLUENCING SLOPE STABILITY

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Purpose: Climate change is constantly posing new challenges to land management with the intensification of extreme weather events such as extreme rainfall. Since these events are among major triggering factors for shallow landslides, even these phenomena will see an increase in their probability of occurrence. In this framework the improvement of soil physical and geotechnical properties for limiting land degradation could be provided through innovative materials such as polymers, that are becoming more and more widespread as they seem promising in preventing soil degradation, reducing the probability of greater damages on human activities and safety, avoiding traditional remediation strategies critical issues. The aim of this work is to present the preliminary results of polyacrylamide (PAM) application on reconstituted soils.

Methods: Two sets of samples were reconstructed using kaolin (Bal-Co spa) and sandy loam (Sabbie Sataf Srl), respectively, with three different dry densities (varying between 10.79 kN/m3and 15.69 kN/m3), and initial water contents (varying between 5% and 40%), and five different polymer application rates (0%, 0.003%, 0.03%, 0.3%, 1% by weight). The polymer, a granular anionic polyacrylamide, provided by Micronizzazione Innovativa Srl, has been manually applied and mixed with the samples, reconstituted in PVC cylinders with a diameter of 9.5 cm and 15 cm high. Samples have then been submitted to volumetric characteristics, and kaolin samples to Atterberg Limits. All tests have been carried out according to ASTM standards.

Results: Not all soil-PAM mixtures exhibited higher Plasticity Index (PI) and Liquid Limit (WL) compared to those of untreated soil. All kaolin samples fell in the area OH-MH/CH, close to the A-line. Lower PAM percentages (0.003%) had little to no consequences on samples PI, while with rising polymer percentages (0.03%, 1%) samples showed rising PI values. WL values for samples containing the lower PAM percentage (65.47) remained close to the average of non-treated samples (64.66), while with rising PAM concentrations they also grew showing remarkably higher values (70.55 and 83.54 with 0.03% and 85.64 for 1%).

Conclusions: The increase of PAM percentage in samples generally coincided with increase of WL and PI, also causing a more delayed release of samples water compared to untreated ones. These preliminary results can stress on the possible application of PAM to improve other soil features (i.e., shear strength properties; water retention curves) which could impact on slope instabilities occurrence. However, preliminary data to date show that PAM-treated samples would retain more water compared to untreated material, therefore further research is needed.

SESSION 3.6

LANDSLIDES PREDICTION: ADVANCED TECHNIQUES AND ALTERNATIVE DATA SOURCES FOR UNCERTAINTY ASSESSMENT AND REDUCTION

UNDERSTANDING THE SEISMIC RESPONSE OF DEBRIS FLOWS USING PHYSICAL MODEL AND NUMERICAL SIMULATION

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Purpose: Large-scale debris flow triggered by extreme climate events or earthquakes can cause significant financial loss downstream. This seriously affects the safety of human life and property. On-site monitoring instruments and equipment are vulnerable to hazards and can experience destruction during a large hazard event, making it difficult for data collection and subsequent early warning. With the development of environmental seismology, it has become an emerging and popular method to discern, analyze and invert the dynamics of debris flow processes by monitoring the seismic signals of debris flow processes. Based on this, researchers can greatly improve the quantitative analysis methods of debris flows.

Methods: This study takes the seismic signal generated by debris flows as the research object. This study develops a new physical model of the seismic signal generated by debris flows considering the basal force through the laboratory flume experiment, combined with numerical simulation.

Results: We have well established the seismic response of debris flows using physical model and numerical simulation.

Conclusions: Furthermore, we can provide theoretical guidance for debris flows and early warning based on seismic signals.

USING ARTIFICIAL NEURAL NETWORKS AND REANALYSIS SOIL MOISTURE DATA FOR DERIVING TRIGGERING THRESHOLDS AND RELATED UNCERTAINTY IN SICILY AND NORWAY

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Purpose: Landslides are a significant geohazard caused by heavy or prolonged rainfall events. The objective of this study is to improve the identification of triggering conditions for landslides using artificial neural networks (ANNs) and the hydro-meteorological concept.

Methods: The procedure used in this study involves three main steps. The first step is the acquisition of rainfall and landslide data, followed by a pre-processing procedure to correct errors and gaps in rainfall measurements. A triggering instant is hypothesized when only limited information is available. In the second step, the reconstruction of rainfall triggering and non-triggering events is performed using the CTRL-T algorithm. A traditional power law threshold is determined, followed by the application of an ANN algorithm for pattern recognition. The ANN is trained on rainfall duration, intensity, and soil moisture data at different depths obtained from the ERA5 Land Reanalysis project. The input data consist of duration (D), cumulated rainfall (E), intensity (I), and ERA5-Land soil moisture data (S) for two study areas. Hourly temporal resolution soil moisture data from the ERA5-Land reanalysis is used at four different soil depth layers. In the final step, a comparison between the thresholds determined with the power law and the ones obtained with the ANN is carried out. The True Skill Statistic (TSS) is used to compare the results of the two approaches.

Results: Results have been derived for Sicily and a group of watersheds in Norway. For the Italian case study, the mean value of TSS is close to 0.7 considering the input data (D-E, D-I, D-E-I) and just a single soil moisture layer. Considering combination of more layers the mean value of TSS increases to values between 0.76 - 0.79. In Norwegian case study the mean TSS with single soil moisture layer is close to 0.66. Considering a combination of more layers leads to and increase of TSS in range 0.76-0.79.

Conclusions: The study demonstrates that ANNs can improve the recognition of conditions that can lead to slope failure by incorporating soil moisture data. The best combinations for recognition rate and calibration uncertainty correspond to input data D-E-SM and D-I-SM.

DETERMINATION OF RAINFALL THRESHOLDS TRIGGERING LANDSLIDES AND PROPOSAL OF A NEW STANDARDIZATION METHOD

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Purpose: Precipitation, especially extreme or prolonged rainfall, is the main triggering factor for landslides worldwide. The occurrence of landslides triggered by rainfall will increase significantly due to climate change with rising short-duration heavy downpours (storms), variations in the hydrological cycle, melting of glaciers in mountains, and other meteorological events. The link between the origin of landslides and rainfall has led to the development of rainfall thresholds. Their objective is to separate triggering conditions (slope instability) above the threshold from non-triggering conditions (slope stability) below the threshold; however, this boundary is never clear.

Methods: Determination of triggering rainfall patterns is mostly based on a single rainfall parameter or a combination of two parameters, which often differ and are not uniform across studies. That makes the results difficult to compare. In addition, most studies consider only days with recorded landslides. They do not consider days when rainfall significantly exceeds the triggering rainfall, and no landslides occur. This leads to the question, “Why did the landslide not occur on a day when the rainfall was more extreme than the triggering rainfall”? After a review of several approaches to establishing a rainfall threshold, we would like to show a more universal approach.

Results: We focused on several individual parameters or combinations of two or more parameters (10- and 15-min intensities, hourly amounts, daily amounts, cumulative amounts, and antecedent precipitation including evapotranspiration for 2, 3, 5, 10, 15, 20, 30, 60, and 90 days), which were set as the best matching thresholds. The level of detail of the threshold analysis also depends on the spatial scale of the study area. The global scale is independent of geological, morphological, land use, or climatic conditions and global thresholds are established simply as a minimum level below which landslides do not occur. The regional scale and regional thresholds are determined for areas extending from a few to several thousand square kilometers. The local scale considers the local geomorphological and climatic setting within an area of hundreds of square kilometers.

Conclusions: Many studies do not offer objective and replicable thresholds with a predictive capability and reliability because of an unclear or completely omitted explanation of the applied landslide or rainfall data and methods. Due to a lack of standards for reporting rainfall parameters, inconsistency exists among the studies. Our new perspective to the rainfall threshold issue compares the entire rainfall pattern with all the calculated rainfall parameters together at the same time. Landslide triggering rainfall values were assessed and they showed a unique match of all the tested rainfall parameters exactly on the day the landslide occurred for the 30-year analyzed period. Rainfall totals that exceeded the landslide triggering rainfall by many times, but no landslide was recorded during them, were also analyzed. It is assumed that a combination of the overall rainfall pattern and the development of the rainfall situation were more important for triggering these landslides than the individual rainfall extremes.

DERIVING HYDRO-METEOROLOGICAL THRESHOLDS FOR SICILY: AN APPROACH BASED ON ERA5-LAND MULTY-LAYER SOIL MOISTURE INFORMATION AND PRINCIPAL COMPONENT ANALYSIS

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Purpose: Thresholds providing the conditions under which a landslide can potentially occur are a key component in Landslide Early Warning systems and thus it is highly important to reduce their uncertainty. The hydro-meteorological approach, which combines rainfall with soil moisture information, has recently gained popularity and is evolving alongside the traditional approach based on rainfall characteristics. Even when multi-layered soil moisture information is readily available from in-situ observations, reanalysis projects, or hydrological models, this information is seldom exploited for deriving hydro-meteorological thresholds, most likely because simpler thresholds, e.g., 2D, are preferred and better understood by decision makers. Considering the limited number of studies dealing with multi-layered information, we here present a methodology, based on principal component analysis (PCA), able to derive 2D hydro-meteorological thresholds that use multi-layer the soil moisture information. A piece-wise linear equation for the threshold is also proposed, being more flexible than the traditional curves, such as the power curve.

Methods: In order to derive such hydro-meteorological thresholds, an inventory of landslides, observed rainfall, and soil moisture data needed to be retrieved. Specifically, the ERA5-Land reanalysis dataset was used, which provides the volume of water at four distinct soil depths levels. Then, PCA allowed to derive the linear combination between soil moisture at different depth layers, retaining as much as possible the information content of the multiple layers together, capitalizing on the presence of correlation between the soil moisture at different depths. Therefore, the hydro-meteorological thresholds employing single- and multi-layer soil moisture data, respectively, were derived using the proposed parametric form of the threshold. Finally, the prediction performances were assessed in terms of receiver operating characteristic (ROC) indices, such as the well-known true skill statistic (TSS).

Results: The case study of the Sicily region was used to test the proposed methodology. Overall, the results obtained corroborated the advantages of the hydro-meteorological approach in comparison with the traditional rainfall thresholds. Specifically, a TSS equal to 0.5 was obtained for the traditional precipitation threshold, while a significantly higher one was obtained for the proposed hydro-meteorological thresholds using multi-layer information (TSS = 0.71). Besides, the comparison of single- and multi-layer threshold performances provided insights into whether shallow or deep soil depth hydrological processes are more or less influent on landslide triggering. In this regard, for the analyzed study area, the multi-layer approach provided similar TSS performances to those obtained with single-layer soil moisture at the upper depths, pointing out that landslide occurrences in Sicily are mostly driven by surface soil moisture.

Conclusions: This study proposed a framework based on PCA for incorporating multi-layer soil moisture information within hydro-meteorological threshold identification, resulting in higher performances than traditional rainfall thresholds. Notwithstanding the uncertainty of reanalysis data, the obtained valuable improvements further encourage the installation of monitoring networks for in situ soil moisture measurements with enhanced spatial and temporal resolutions. Future developments will consider other geographical regions in order to further explore the role of multi-layer soil moisture.

FULL UNCERTAINTY PROPAGATION ESTIMATES IN SHALLOW LANDSLIDE SIMULATIONS: FROM STATISTICS TO PHYSICALLY-BASED MODELLING

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Purpose: Physically-based simulations of shallow landslides (e.g., debris flows or debris slides) rely on data input often obtained using statistical methods. Generally, the required parameters consist among others in hydraulic conductivity, soil depth, shear strength. These are commonly collected at discrete locations, interpolated and then fed as spatially continuous maps into the physically-based simulation models. Then, some sort of uncertainty estimation takes place, albeit rarely, to assess the limitations of the hydro-mechanical equations in simulating slope failures and their evolution in space and time. However, a fundamental aspect is completely neglected:, namely the fact that even interpolators are not perfect solutions, and that they also come with their own uncertainty. Neglecting this aspect implies that even the few experiments where uncertainty is studied regarding the physical components, are not rigorous enough to represent the full uncertainty in the simulation procedure as a whole. This work attempts for the first time to implement a Bayesian version of a Kriging interpolator, used to simulate a large number of parameter maps. Then each one of these maps is passed to the physically-based model. This ensures that the uncertainty in the statistical pre-processing passes to the next deterministic step, ultimately producing an ensemble of shallow landslide simulations whose mean and standard deviations are representative of the full modelling uncertainty.

Methods: To interpolate hydrological and geotechnical parameters obtained in the catchment of Vernazza (Italy) we used R-INLA (Integrated Nested Laplace approximation) and an SPDe (Stochastic Partial Differential equation) approach. Tens of posterior simulations (tens of maps) for each parameter are then performed and stored. These layers constitute the entries to be passed to OpenLisem, where slope failure, entrainment, runout and deposition are simulated. Each output is stored separately and the overall summary statistics are ultimately computed to measure the mean simulation as well as the (full) uncertainty around it.

Results: Full uncertainty estimation is a topic that usually belongs to the use of Markov chain Monte Carlo simulations. Here we replicate an analogous idea but chaining the uncertainty in the statistical component together with the one that pertains to the physically-based modeling. The results are much more informative as compared to the standard outputs one can find in the literature for slope and catchment solutions.

Conclusions: We propose a full uncertainty estimation as a crucial element to be considered part of any landslide simulation. The procedure is extremely cumbersome and time consuming though, and even in our case, we had to assume some approximations. The future though is quite promising as distributed calculations over multiple processors could speed-up the overall procedure and makes this single site-specific experiment a standard even elsewhere and for other processes.

IMAGE RECOGNITION ALGORITHMS AND DEEP LEARNING FOR FORECASTING THE SURFICIAL DISPLACEMENTS OF A SNOW MELTING AFFECTED LANDSLIDE

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Purpose: The most of landslide-prone areas spread in mountainous areas with abundant rainfall. However, when high altitudes make areas prone to significant snowfall, the amount of such precipitation, as well as environmental temperature and humidity, should be taken into consideration to determine its effect on the condition of landslide stability. In fact, the melting of relevant volumes of snowfall on the slope may act as one of triggers for landslide displacements.

Methods: To pursue this aim, the present study focuses on the quantification of snow accumulation on the slope through approaches based on image recognition algorithms and on the prediction of surface displacements of the slope using two-steps LSTM (Long short-term memory) neural network. Within this model, the presence and the change of the snow is evaluated by means of a series of image-processing algorithms aiming at calculating the cover square percentage of snow in the RGB image, especially filtering out the noises from white-shown rocks. Subsequently, the main LSTM aims at forecasting the landslide displacement in the future 12 hours using as input the past 5 days data of rainfall, snowfall and movements of the slope. The necessity of estimation of the change of the snow condition makes it necessary to implement a secondary LSTM for estimating if the snow coverage is going to accumulate or melt in next 12 hours, again basing on the past 5 days environmental measurements (temperature and humidity). Both the LSTM are trained basing on the historical measurements of temperature, humidity, rainfall, snowfall and landslide displacement.

Results: The snow is separated from the white-shown rocks by the snow recognition algorithms that give the quantification index to be used as one of input data to LSTM. Two-steps LSTM is feasible to forecast the displacement tendency with reference value.

Conclusions: The images recognition algorithms successfully quantify the snow coverage and the two-steps LSTM implementation achieves the forecasting of the landslide displacements, focusing in particularly on the effects of snow melting in the stability condition of the slope.

UTILIZING ENSEMBLE MACHINE LEARNING FOR LANDSLIDE SUSCEPTIBILITY MAPPING AND THE LHASA MODEL FOR LANDSLIDE NOWCASTING IN NEPAL HIMALAYA

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Purpose: Landslides are becoming increasingly common in Nepal, and their incidence is expected to grow as precipitation patterns become more severe and road-building increases. Thus, the growing levels of danger from landslides caused by hydro-meteorological variability result in severe loss of life and property damages and severe damage to the vital economic systems of the Himalayan nation. Unfortunately, Nepal's demographic condition remains a significant obstacle to measuring vulnerability and risk, as real-time network monitoring, whether to collect field data or connect to warning systems, is rare. The research deals with landslide analysis and subsequent development and implementation of regional nowcast early warning systems in the Nepal Himalaya.

Methods: This study utilizes an integrated approach that combines two modeling methods. The first method involves using a probabilistic ensemble approach that combines three models - Multivariate Adaptive Regression Splines (MARS), Adaptive Boosting (AB), and Random Forest (RF) - to predict the likelihood of landslide occurrences. The models incorporate multiple causative factors (CFs) and utilize data on geo-environmental factors related to landslide occurrence. The second method involves developing a near-real-time landslide warning system by integrating the results of the landslide susceptibility modeling with decision tree-based selection criteria. To support the modeling procedures in this research, independent variables obtained from terrain analysis were included. Additionally, a global Landslide Hazard Assessment model for Situational Awareness (LHASA) was utilized to indicate where and when landslides may be likely in the study area. After preparing the final ensemble-based landslide susceptibility maps, a landslide Nowcast system was developed in Google Earth Engine (GEE) platform.

Results: The outcomes show a common pattern, ensuring that with an increase in the index value, the occurrence of the probability of the landslide also increases, i.e., a higher index represents a higher susceptibility to landslide occurrence. The highly susceptible area is more confined near to the drainage and steep areas. The flat and gentle slopes represent the low susceptible areas. The results of three model was combined with generalized linear model (GLM) for better prediction. The area under ROC curve shows the result of ensemble model is better than any solo result of utilized three models. The accuracy is 87%. The ensemble landslide susceptibility maps were classified using natural break algorithm in GIS platform. Total of 69.72 % of the area was categorized as having a very low susceptibility, 16.01 % as low susceptible, 6.84% as moderate, 4.07% as high and the remaining 3.36 % was considered have very high susceptibility. About 81.51 % of landslide data were located in the very-high-susceptibility class, demonstrating the reliability of the map.

Conclusions: Thousands of landslides were occurred and thousands of peoples were died during 2015 Gorkha Earthquake. So the possible problems that may come due to these natural processes like heavy rainfall shouldn’t be ignored.

GEOSTATISTICAL METHODS AND ARTIFICIAL NEURAL NETWORKS FOR LANDSLIDE HAZARD PREDICTION – THE EXAMPLE OF KRAKÓW CITY

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Purpose: The aim of the study was to quantify a landslide hazard (H; understood as the probability of a landslide occurrence within a specified period of time and a given place) in an urbanized area with a complex geological conditions.

Methods: Landslides that were active in the years 1969 – 2019 were identified with the analysis of the numerical differential terrain models and available archival data (landslide registers, orthophotomaps, geological and engineering documentations, landslide monitoring reports, publications). Based on the observed correlation between the landslides distance and their activity, the technique of areal binomial kriging available in Geostatistical Wizard module (ArcGIS) was implemented to create a time probability model (TPM) of the landslides occurrence in the next fifty years. Due to the differentiation of landslide types in the study area, a multi-layer perceptron was used to determine the landslide susceptibility model (LSM). The learning process was performed in the r.landslide module using 8 thematic layers: slopes, slopes exposure, absolute height, relative height, convergence index, surface lithology, sub-Quaternary lithology, distance from tectonic discontinuities. The one-at-a-time sensitivity analysis of the thematic layers was also carried out. The landslide hazard map of Kraków was obtained by multiplying TPM and LSM.

Results: About 11% of Kraków area is covered by areas where the probability of a landslide occurrence in the years 2020 – 2070 exceeds the value of 0.2. The greatest hazard (H > 0.6) occurs in the southern part of the city. In the case of area located in the central part of the city, the hazard values seem to be slightly overestimated by the applied kriging algorithm. The sensitivity analysis showed that among the thematic layers used for modelling the slopes, convergence index, distance from tectonic discontinuities and the sub-Quaternary lithology have the greatest impact on the landslide occurrence in Kraków area.

Conclusions: An artificial neural networks are useful in determining the landslide susceptibility in areas with complex geological structure and topography, with various types of landslides. Geostatistical methods may lead to local overestimation of the time probability model values in the areas of scattered landslides, constituting single occurrences unrelated to the natural predispositions of a given area to the formation of mass movements.

UNCERTAINTY ANALYSIS OF LANDSLIDE SUSCEPTIBILITY MODELS UNDER THE INFLUENCE OF SAMPLE SIZE

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Purpose: Landslide susceptibility assessment is an effective technique for landslide prevention and mitigation. Currently, the main feasible methods of landslide susceptibility evaluation on a large scale are data-driven methods. Most researchers have devoted themselves to improve model performance. However, there is also a very important issue about how to measure the performance of landslide susceptibility models. At present, the performance evaluation metrics of susceptibility models are derived from machine learning, mostly through confusion matrix and ROC curves, and there are few metrics that take into account model uncertainty and the actual meaning of landslide susceptibility. The purpose of this paper is to explore a model evaluation index that considers the practical implications and uncertainties of landslide susceptibility.

Methods: Based on the general assumption of machine learning models, the accuracy of the model is positively correlated with the number of labeled data in the case of accurate labeling. Therefore, we consider that when the susceptibility level of a raster varies regularly with the increase of the number of samples, the landslide susceptibility level of the raster is determined. The result of the last evaluation is used as the susceptibility level of the raster, otherwise the susceptibility level is uncertain. The quotient of the number of grids with determined susceptibility level and the total number of grids can be used to evaluate the model performance, which is defined as the susceptibility zonation determination ratio (SZDR). Taking Wanzhou district as an example, three models of information value, neural network, and random forest were selected, and nine factors were chosen for three times of susceptibility evaluation. The samples were different for each evaluation. The 80%, 90%, and 100% of the number of landslide raters were selected as positive samples in turn, and the same number of negative samples were selected using a screening strategy. The results of the susceptibility assessment were classified into five categories using the natural breakpoint method. In this case, if the susceptibility class of a raster in the second evaluation is between the first and the third, including the same as the first or the third, it's susceptibility class can be considered to be regularly changing.

Results: The statistical results show that the AUC values of the three models increased in the three evaluations, but the increase was not significant. The sequence of AUC values from largest to smallest is: random forest, neural network, and information value, which of the susceptibility zonation determination ratio (SZDR) is: information value, random forest, neural network.

Conclusions: It is biased to judge the performance of the susceptibility model only based on the AUC value, and it is also necessary to consider the susceptibility zonation determination. Although the information value model has lower evaluation accuracy, it can well reduce the uncertainty of the model.

NUMERICAL MODELLING OF GLACIER LAKE OUTBURST FLOODS: PROCESSES AND RELATED UNCERTAINTIES

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Purpose: Glacier lake outburst floods (GLOFs) are considered among the most dangerous glacier hazards worldwide. The variability in flow magnitudes and the ability to transform into powerful debris flows pose challenges to affected regions and have caused fatalities and infrastructural damage in several regions across the globe. In recent years, the efforts in modelling GLOF dynamics have increased and a variety of modelling approaches were used to approximate realistic flow behaviour to estimate possible runout distances and other flow characteristics.

Fig. 1: conceptual model for the sensitivity analysis with the three main domains investigated.

Input hydrograph experiment	
Total volume V_{tot}	10 - 200 $[m^3]$
Maximum discharge Q_{max}	5 - 100 $[m^3\,s^{-1}]$
Initial velocity v_0	2 - 20 $[m\,s^{-1}]$
Drainage time t_{hydro}	10 - $t_{end}/5$ $[s]$
Entrainment experiment	
critical shear stress τ_c	0.5 - 1.5 $[kPa]$
potential erosion height $[m]$	0 - 3 $[m]$
Variable erosion areas	Zone 1, 2, and 3 ^{a}
Modelling strategy experiment	
μ	0.02 - 0.08
ξ	400 - 1200
two-phase	$\mu, \xi = f(\phi_s, \phi_l, t)$

Table 1: parameters investigated in this study and their value's range.

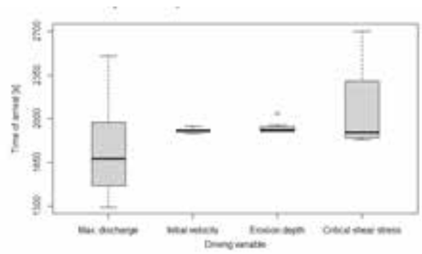

Fig. 2: example plot of the sensitivity analysis.

Methods: In this study, we apply the single-phase numerical modelling software RAMMS debris flow to the simulation of GLOFs and we investigate its sensitivity to uncertainties in physical processes, mainly related to three domains: i) outburst mechanism, ii) flow propagation, and iii) flow transformations (Figure 1). For the first, we investigate: total input volume, maximum discharge value, initial velocity, and outburst duration. For the second, we investigate: critical shear stress, erosion rates, and potential erosion depth. For the latter, we define ad hoc four different scenarios, ranging throughout the parameter space given by the literature, and show how different mass movement can be obtained by their combination. Additionally, we investigate the application of a two-phase research version of the software, which allows for the description of differential deposition and phase transformations. As a study case, we adopt the well documented Aksai valley and the periodic outburst of the Uchitel glacier lake, Kyrgystan.

Results: Our analysis resolves quantitatively the influence of parameter uncertainty on modelling results. The most important parameters are evidently the initial flow volume and the critical shear stress. Other variables, such as the initial flow velocity and the maximum erosion depth have a lower impact on the results (Figure 2). In general, the uncertainty in the initial conditions, and in the modelling strategy, can lead to very distinct mass movements, with strong implications for hazard and risk assessment. Further, it is demonstrated how sediment entrainment can reduce travel times by up to 50% while also altering flow parameters. Although the single-phase version of RAMMS allows modelling entrainment, results are limited when it comes to differentiating between solid and fluid phases, which increases the uncertainty when modelling non stationary processes with phase changes and flow separation. The dynamics and impacts of flow transformations can therefore only be approximated under certain assumptions. Future studies and hazard assessments shall therefore focus on understanding parameter interactions better and on modelling flow type transformations using multi-phase models.

Conclusions: The systematic analysis allows to derive conclusions beyond the study case, until the physical interpretation of the link between model parameters and physical processes. In conclusion, we suggest a possible procedure and practical indications for the assessment of modelling uncertainties in the context of GLOF simulations with the one phase software RAMMS debris flow.

EXPERIMENTS OF MODELLING SUBAQUEOUS LANDSLIDE SUSCEPTIBILITY IN LAKE ALBANO OF CASTEL GANDOLFO

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Our modelling experiments are to generate and interpret the prediction patterns of subaqueous landslide forms in the Lake Albano maar, a complex volcanic depression. The patterns, that rank the likelihood of future events, relate the spatial distribution of historical forms inside the lake with the values of continuous fields derived from a high-resolution digital elevation model. We established the spatial support for modelling the patterns by empirical likelihood ratios and used two mathematical models for integration of spatial relationships in the presence and in the absence of landslide forms: a fuzzy set function and a logistic discriminant function. The lake area covers 6 Km2, has the coastline at 290 m a. s. l., reaches a maximum depth of 167 m and contains 42 linear and 23 polygonal subaqueous landslide forms. They occurred in historical times, i.e. from 2100 years ago to the present. We constructed a raster database at high resolution to represent the location of the landslide forms, generated a digital elevation image and derived six topographic-surface continuous fields over the lake area: aspect, dtm, slope, curvature, planform and profile. Evaluation of modelled prediction patterns is by sequential exclusion of one landslide occurrence from each dynamic type of form to generate cross validations with partial prediction patterns. After comparing the prediction-patterns relative ranks, we subject them to sensitivity analysis and to geological interpretation. Discussion of the results is in the context of lahar deposits and of suspected catastrophic floods that affected the volcanic crater of Lake Albano in Roman time, i.e. 398 B.C. That multi-hazard context may still represent serious risks to the urbanization and recreation activities of the area surrounding the presently dormant volcanic crater.

SESSION 1.7

CULTURAL HERITAGE THREATENED BY LANDSLIDES: FROM EARTH OBSERVATION AND IN SITU INVESTIGATION TO SUSTAINABLE MITIGATION MEASURES

COSMO-SKYMED FOR CULTURAL HERITAGE THREATENED BY GEOHAZARDS: CURRENT TECHNOLOGIES AND RETURN OF EXPERIENCE FROM OPERATIONAL IMPLEMENTATION

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Purpose: Interferometric Synthetic Aperture Radar (InSAR) proves effective for monitoring cultural heritage affected by geohazards [1]. Italian Space Agency (ASI)'s COSMO-SkyMed constellation suits this purpose thanks to its huge archives of SAR data, high spatial resolution and weekly revisit time [2]. In the Copernicus Programme, COSMO-SkyMed is the Contributing Mission with the steadily growing trend of exploitation in this application domain [3].

The paper aims to:

(i) showcase the lessons learnt from successful operational implementation in heritage sites by ASI and the UNESCO Chair on Prevention and Sustainable Management of Geo-hydrological Hazards at the University of Florence;

(ii) outline the most technological advances brought by COSMO-SkyMed Second Generation (CSG) satellites towards the definition of best practices.

Methods: Experience was gathered in the framework of national initiatives, the most recent of which is the Extraordinary Plan of Monitoring and Conservation of Immovable Cultural Heritage funded by the Italian Ministry of Culture. The case studies, distributed across Italy, were investigated with Persistent Scatterer Interferometry (PSI) time series generated by processing long datasets of COSMO-SkyMed first and second generation satellites that were mostly collected via the Map Italy project since 2011 and 2021, respectively. The condition assessment of the heritage assets affected by geohazards was performed using satellite PSI-based methodologies that were implemented and already tested in scientific literature for evaluating potential building deformation and settlement at local scale. In particular, the stability and potential deformation on built-up fabric at the single manufact scale are analyzed by considering deformation rates revealed by InSAR measurements on each structure and cross-compared with background geological data, constructive features and on-field evidences. Moreover, PS deformation estimates within each building are converted into indexes whose range classes can rate the manufact instability.

Results and Conclusions: From a technical point of view, the implementation in the case studies of some historical built-up areas, e.g. Pienza, Volterra and Orvieto, has shown that PSI data from COSMO-SkyMed imagery can rapidly point out the highest deformations rates and most hazardous sites over the historical and cultural heritage sites and surrounding territories. PSI-based indexes allowed to categorize the deformation health of manufacts, thus providing a remotely-sensed support for condition assessment and proper management planning.With regard to the user-uptake, during the collaboration with the Archaeological Park of Colosseum, the COSMO-SkyMed first generation InSAR deformation time series were directly ingested in the SyPEAH WebAPP system [4] developed by the Park itself as a tool for an effective activity of programmed conservation of the archaeological structures. The system serves for ground validation of satellite data, in order to define a protocol that could be replicated on a larger scale. This experience proves how COSMO-SkyMed data can be directly ingested into the institutional user workflow, instead of remaining a dataset interpreted externally to the decision-making process, as unfortunately may happen in research-focused studies or consultancies.

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SATELLITE MONITORING OF CULTURAL HERITAGE THREATEN BY LANDSLIDE IN ITALY

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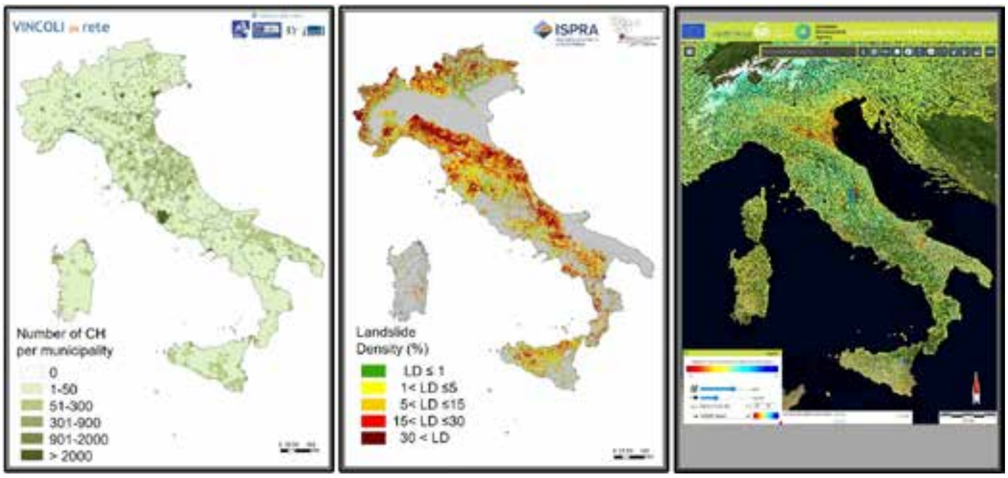
Italy is the country that owns most of the world cultural heritage and at the same time is affected by a very large number of landslides widespread throughout its territory. The present work is part of the activities carried out between ISPRA and Ministry of Culture - General Directorate for the Safety of Cultural Heritage, in the general framework of the implementation of the first “Extraordinary National plan for monitoring and conservation of Italian Cultural Heritage”. The plan aims at the conservation and protection of cultural heritage, and specifically at its safeguarding towards the impacts of different hazards, both natural and anthropogenic, including climate-induced extreme events. One of the topics is to implement both remote and in situ integrated monitoring systems of the most vulnerable monuments and sites (e.g. bell towers, monumental complexes, archaeological areas in urban, coastal and remote areas) taking into account structural and environmental different level of risks.



Scope of the work is to define a GIS based methodology in order to assess cultural heritage exposed to very slow mass movements by integrating SAR data, the Italian Cultural Heritage database (VIR) and the Italian Landslide Inventory. The methodology has been tested first at a regional level. More in detail the present works aims at analysing satellite data coming from the European Ground Motion Service (EGMS) with respect to national Cultural Heritage distribution, potentially affected by morphological process (e.g. landslide and subsidence) or structural problems. The EGMS provides ground deformation products at Pan-European level with millimetre accuracy and is based on the multi-temporal interferometric analysis of Sentinel-1 radar images at full resolution (years 2015-2021). The National Cultural Heritage distribution was obtained from Carta del rischio and Vincoli in Rete datasets (http://vincoliinrete.beniculturali.it), implemented since 1992 by the Central Institute for Restoration, which contains more than 200,000 features. The slow mass movements were obtained by querying and processing data coming from the Italian Landslide Inventory (https://idrogeo.isprambiente.it/app/iffi), carried out by ISPRA and by the Regions and Autonomous Provinces since 1999, which contains more than 620,000 landslides.

The main results were on one hand verifying the usability of the data coming from the European Ground Motion Service jointly with the datasets currently available at national scale related to landslides and their potential interactions with the Cultural Heritage. At the same time it was possible to define an iterative procedure for the automatic identification of deformation anomalies (displacements and time series velocity) affecting areas with the presence of Cultural Heritage.

Satellite monitoring of landslides over large area, in near real time, is one of the national and global challenges for reducing the effects induced by climate change on Cultural Heritage exposed to natural hazard. In order to achieve these goals, Italy is preparing to implement a specific downstream satellite monitoring service with high spatial resolution and high temporal frequency. This study aims at testing at national level the capability for the use of new space technologies for ground deformation monitoring and the relation with strategic assets such as Cultural Heritage.

INSAR MONITORING OF SLOPE INSTABILITIES IN THE ARCHAEOLOGICAL PARK OF PHLAEGREAN FIELDS

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Purpose: The present work is part of the activities carried out by ISPRA and Ministry of Culture – (General Directorate for the Safety of Cultural Heritage), in the general framework of the implementation of the first "Extraordinary National plan for monitoring and conservation of Italian cultural heritage". The Plan is aimed at the conservation and protection of cultural heritage, and specifically on its protection against the impacts of different hazards, both anthropogenic and natural, including climate-induced extreme events.

Methods: More in detail, a specific Interferometric Synthetic Aperture Radar (InSAR) analysis has been implemented in the archaeological area of the Phlegrean Fields, a coastal region in southern Italy located in an active caldera near Naples, to investigate potential ground deformation phenomena. The study is focused on the period between 2016 and 2020 using Sentinel-1 SAR data to generate ground displacement measurement points (Persistent Scatterers with times series) and to analyze their spatial distribution and correlation with slope instability and archaeological remains damages.

Results: First result shows significant deformation patterns in the area, with vertical uplift rates up to 50 mm/year in the central volcanic area (Pozzuoli). The analysis yields numerous but not exhaustive information about the presence of small-scale landslide phenomena in the surroundings of the Roman Thermae of Baia. Then an InSAR analysis using high-definition Cosmo-SkyMed SAR data has been performed, in order to derive information on small scale landslides by comparing the time series made with CSK and SENTINEL data. The CSK data are in X-band (wavelength 3.1 cm) and have a spatial resolution of 3 meters, much precise than Sentinel1 (20 meters), with the ability to detect even smaller displacements affecting archaeological structures (e.g. walls, roof, caves and rock structures). The dataset consists of Images (57) descending and (60) ascending scenes in the time period from 2017 to 2021. Data processing has been performed using the Interferometric synthetic aperture radar Scientific Computing Environment (ISCE), the Stanford Method of Persistent Scatterers (StaMPS) and TRAIN Toolbox for Reducing Atmospheric InSAR Noise. Moreover results data have been calibrated by local GNSS network data.

Conclusions: CSK data results provide useful elements to confirm current uplift trend in the entire Phlegraean Fields area in accordance with Sentinel data. After a recent extraordinary clearing of the slope from vegetation, the overall stability condition was better clarified. InSAR analysis provides very useful informations to detect and monitor ground displacements, thus offering to archaeological site managers a powerful tool for the prevention of ground related damage of cultural heritage.

SLOPE STABILITY ASSESSMENT OF THE NIKOLSKAYA MOUNTAIN IN THE MOZHAISK KREMLIN

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The history of the Mozhaisk Kremlin counts several centuries. Currently there are Novo-Nikolsky and Peter and Paul's Cathedrals located on the Kremlin territory. Novo-Nikolsky Cathedral was built in the style of pseudo-gothic, or Russian gothic, by architect A.N. Bakarev. Its feature is that Cathedral is built around the ancient gates and the gate church of St. Nicholas built in 1685, from which it got its name. The cathedral is an object of cultural heritage of federal significance. In April 2013 a landslide came down a few meters from the southwestern corner of the cathedral.

In geomorphological terms the work site is located on the Kremlin hill (Nikolskaya Gora) within the Smolensk-Moscow morainic-erosion upland, divided by deep river valleys and ravines. The relief of the site is hilly, the marks are about 183 - 190 m at the foothills and about 202-203 m at the edge and upper part of the hill. The hill slope has a significant steepness (about 41°) and height (13-19 m). The surface of the slope is flat, without mounds and bumps, overgrown with grass.

In structural terms the territory is located within Moscow syneclise.

In the geological structure to a depth of 35 m modern technogenic accumulations (tQIV) and glaciolacustrine deposits (lgQIIms1-2) take part.

Underground waters within the studied section are represented by two aquifers distributed everywhere: the main aquifer, dedicated to dusty sands and loam of glaciolacustrine deposits (lgQIIms1-2) and temporary perched water.

During the settled landslide examination, it was found that it was formed on the border of the glaciolacustrine deposits and technogenic soils. The contact zone was represented by soils with high humidity.

The stability assessment of the slopes made of technogenic soils has a number of features.

In the process of forming an array of technogenic soils, layers and lenses can be formed filled with accumulations with unpredictable mechanical properties. The heterogeneity and unpredictability of the composition as a rule does not allow the assumption about the soil properties distribution within the complex of technological accumulations. And when calculating the stability of such slopes one must consider low (compared to the average value) strength properties, as they play the role of a "weak link", according to which the development of a potential sliding surface is possible.

For this reason, the calculations of such slopes' stability are preferably to perform with creating either the fields of the soil properties distribution or using RLEM.

The slope stability assessment made in 2014 made it possible to design engineering protection measures that perform their functions properly.

THE APPLICATION OF A PB SLOPE STABILITY MODEL FOR THE CONSERVATION OF CULTURAL HERITAGE: THE CASE STUDY OF THE ARCHAELOGICAL SITE OF PIETRABBONDANTE

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With a cultural heritage of the most varied in the world, Italy counts on presence of 3,400 museums, 2,100 archaeological sites, 24 national parks, 23 marine areas and 55 World Heritage sites [Research Italy]. However, the cultural heritage is constantly exposed to agents able to compromise its conservation; in addition to natural deterioration and anthropic impact, environmental changes and climatic conditions represent an important risk for the cultural heritage preservation.

In this contribution the attention is focused on the archaeological heritage, consisting of a set of artefacts erected by man. In the past, these artefacts constituted buildings, while today, they contribute to enrich national and international cultural heritage creating the archaeological sites.

Several archaeological sites are constantly threated by geological and geomorphological problems [Lollino G. et al., 2006]; the archaeological area of the Valle dei Templi [Cotecchia V. et al., 2005], the Ninfeo di Genazzano [Amorosi A. et al., 2015], the Archaeological area of Pompeii [Pompei, 2015], the area of Ostia Antica [Cecchi R., 2014], represent some Italian emblematic cases for type of movements and extension of involved assets. These monuments appear as static entities located in the areas subject to dynamic processes of the soil; the kinematics movements of the soil covers pose a threat to monuments and visitors.

Given the importance of archaeological sites, for the testimony of human life that represent, this contribution wants to highlight the important role of geotechnical engineering for the conservation and safeguard of archaeological assets.

The paper describes the application of a physically based (PB) approach to evaluate the stability conditions of the archaeological site of Pietrabbondante (Molise region). In this work MAT-TRIGRS code [Ma Siyuan et al, 2021] has been modified in order to implement the partially saturated conditions of the soil and to evaluate the effect of the soil saturation on slope stability. Forecasted rainfall events have been used to estimate the spatial distribution of FS (Factor of safety).

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IS THE BRAZILIAN PRECOLONIAL ARCHAEOLOGICAL HERITAGE IN DANGER? REGIONAL-SCALE LANDSLIDE SUSCEPTIBILITY ASSESSMENT IN THE SERRA DA CAPIVARA (PIAUÍ STATE) AND THE SERRA DO MAR (SÃO PAULO STATE)

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Purpose: Cultural and natural heritage sites' integrity, value, and accessibility may be threatened by landslides and several studies were aimed to understand those threats, mainly in Europe. Studies with this purpose remain scarce in Brazil, where landslides studies usually focus on quantifying the potential damages to infrastructural and human assets. Hence, there is a gap in the production of landslide hazard cartography based on quantitative models and aimed to safeguard the Brazilian cultural heritage. The central objective of this research was to assess the landslide susceptibility in Brazilian pre-colonial sites in different morphostructural and climatic settings using quantitative models at regional-scale, as a preliminary step to define critical areas for local-scale studies.

Methods: Two Experimental Areas were selected to assess landslide susceptibility at the regional-scale: the Serra do Mar and Ilhabela State Parks, an Atlantic Forest biodiversity hotspot on the humid-tropical Southeast coast of Brazil (São Paulo State), and the Serra da Capivara National Park (Northeast Brazil, Piauí State), in the biogeographical ecotonal zone between the semiarid Caatingas and the wet/dry subhumid Cerrados. These areas are recognized as susceptible to shallow landslides associated with debris flows and rockfalls, respectively. They also host relevant archaeological sites for the chronology of the human occupation of the South American continent, and our hypothesis is that some of those sites may be threatened by landslides. Precompiled shallow landslides inventories and an empirical rockfall source-areas inventory were used to deploy a logistic regression model with a repeated k-fold cross-validation strategy, using open-source Digital Elevation data and software. Explanatory variables were selected based on expert knowledge and on a multicollinearity diagnosis using the Variance Inflation Index. Archaeological site's location was obtained through public datasets and through an extensive literature review aimed to bridge the incompleteness of the public data in the Serra do Mar Area.

Results: Our models displayed high accuracy (> 0.85 for the Area Under the ROC Curve – AUC ROC) and robustness (less than 0.02 for the Interquartile Range of AUC ROC values calculated during cross-validation). Our results show that 7 out of 73 precolonial archaeological sites in the Serra do Mar Area are potentially threatened by landslides, mainly the thin shell-middens located on the small continental islands of the São Sebastião Archipelago, which can be faced with rockfalls. In the Serra da Capivara Area, 120 out of 624 archaeological sites are potentially threatened by rockfalls, mainly rupestrian painting sites on rock shelters located along the Pedra Furada Valley.

Conclusions: Therefore, we conclude that those two areas (the small islands of the São Sebastião Archipelago and the Pedra Furada Valley) are critical to perform detailed landslide hazard studies and field campaigns aiming to understand the degree of threat posed by landslides to the archaeological sites' integrity.

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ASSESSMENT OF RECENT LANDSLIDE HAZARD AND BLOCK MOVEMENTS AT THE SERAPEUM TOMB IN SAQQARA - EGYPT

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The Serapeum is considered historically as the tomb of burial the arks of the sacred bulls of the “Apis” cult at Memphis. It was believed that the bulls were incarnations of the God Ptah, which would become immortal after death.

Over a timespan of circa 1400 years, from the New Kingdom to the Ptolemaic Period, at least sixty Apis are attested to have been interred at the Serapeum. The earliest burials are found in isolated tombs. As the cult gained importance, underground galleries were dug to connect subsequent burial chambers. One of the cult practices involved the dedication of commemorative stone tablets with dates relating to the life and death of the “Apis”.

The Serapeum is a valuable archaeological unit that has been subjected to serious structural damages and deterioration due to its existence in a succession of marl, limestone, and shale, as the shale swells with the change of the water table and causes change in principal stresses orientations around the galleries and the openings. Engineering stress analysis, and numerical modeling of the underground tomb dates back to the 1980’s, while it was later in the 2000’s that a major restoration and consolidation project have started to ensure the safety of the tomb and the stability of the roofs, and the tomb itself.

In this paper, we revisit the stability of the tomb from a numerical analysis point of view, determine sensitive zones to instability, and assess the adequacy of the installed support structures.

LANDSLIDES RISK ASSESSMENT IN ALULA ARCHAEOLOGICAL SITES (KINGDOM OF SAUDI ARABIA)

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Purpose: The present work is mainly focused on the assessment of the potential geo-hazards affecting the AlUla region. Located at 1.100 km West from Riyadh, AlUla covers an archaeological area of more than 22.000 mq (2,2 ha), where is possible to walk in a luxuriant oasis passing by ancient world heritage site through rock cut landscape shaped for thousand years. Its best-known site is Hegra, the first UNESCO World Heritage Site in Saudi Arabia, main southern city of the Nabataean kingdom, and a Roman outpost, that conserves over 110 monumental tombs which elaborated facades are carved into the sandstone rock. In addition to Hegra, AlUla hosts a number of other fascinating historical and archaeological sites such as its Old Town, surrounded by an ancient oasis; Dadan, the capital of the Dadan and Lihyan kingdoms, considered one of the most developed cities of the first millennium BC in the Arabian Peninsula; and many ancient rock-art sites (e.g. Abu Ud, Jabal Ikmah). Local structural condition promotes potential instabilities (e.g., rockfall, sliding, toppling) that may involve unstable volumes. These instabilities may affect both heritage and visitors. Due to this possibility, an assessment of potential geo-hazards in the AlUla region has been funded by local authorities, i.e. the Royal Commission for AlUla.

Methods: The adopted methodology was following different analysis scales, depending on the threat, from micro scale (e.g. weathering) to general processes scale (e.g., landslide, floods) involving large areas. The general approach, implemented in the conservation activities of rupestrian sites and followed in this research, includes a detailed interdisciplinary study, to understand rock degradation processes and causative factors, followed by field conservation work. During field surveys, many weathering and alteration processes affected different heritage sites, as well as structural setting (bedding, joints, faults), mainly related to stratigraphical setting, tectonic activity, and geomorphological evolution of the slope, were recognized and classified also by means of high resolution laser scanning. Laboratory test campaign was performed for the two main geological material outcropping in the whole area (Quweira Group, yellowish sandstone and the Siq Group, red sandstone) to define main physical and mechanical proprieties and parameters.

Results: All the above mentioned aims to reconstruct any instability conditions of the rock facades, providing a preliminary assessment of landslide kinematics and potential geo-hazard that may affect our Heritage sites. A guideline for consolidation has been provided to the Authorities and will be implemented in critical sites. The final step will consider the mitigation and consolidation of potential threats, that is mainly related to sustainable practices, possibly also based on the application of local conservation techniques.

Conclusions: The present paper has the main scope of developing a first analysis of the geomorphological evidences, the mechanical properties of the rock materials, the rock slope instabilities and main threats affecting the cultural heritage sites in AlUla. Preliminary short and long term mitigation actions (both structural and non structural) were suggested in order to develop a future conservation management plan.

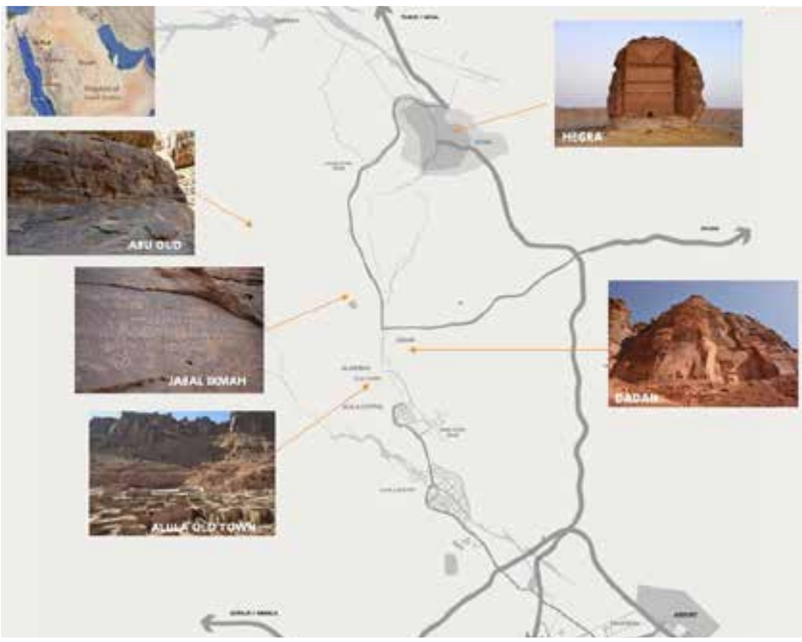

Fig. 1: Map of AlUla investigated archaeological sites.

SESSION 2.9

PAST, PRESENT AND FUTURE OF SATELLITE INTERFEROMETRY FOR LANDSLIDES (part II)

TOOLS FOR AN EASY EXPLOITATION OF THE COPERNICUS EUROPEAN GROUND MOTION SERVICE (EGMS) - THE RASTOOL PROJECT

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Background: After the launch of Sentinel-1 in 2014, the new Copernicus European Ground Motion Service (EGMS), available since May 2022, represents a new key turning point in the use and application of satellite interferometry. We are going toward an increasing free and open policy availability of data and products. The EGMS freely provides consistent, regular (with yearly updates), and reliable information regarding natural and anthropogenic ground motion phenomena over the whole Europe, with millimetre accuracy (https://land.copernicus.eu/pan-european/european-ground-motion-service). EGMS represents a free and rich source of knowledge for the geohazard community and territorial managers. Nevertheless, the full exploitation of this amount of information is time consuming, demanding a high level of expertise and a specific background.

Purpose: The aim of this work is to present RASTOOL (EGMS RASTOOL: European ground motion risk assessment tool), a project co-financed by the EU-Union Civil Protection Mechanism. RASTOOL aims to develop a set of tools for simplifying the EGMS data use, to automatically analyse them and to generate maps to support hazard, exposure, and risk-assessment against geohazards (both natural and anthropogenic).

Method: Starting from the tools developed in the frame of previous projects (Safety, U-Geohaz, MOMIT), they are being improved to be easily applied to the EGMS products and integrated with new ones. Just as an example, the EGMS maps can be downloaded as a set of csv files, the downloaded area is divided into sub-areas (corresponding to bursts of one or more frames), implying the adaptation of the tools application to this kind of "fragmented" input. The first tool we present is the ADAFinder, which starting from the EGMS measurement points, automatically extracts only the Active Deformation Areas (ADA) polygons. The other tool that we present is the ADAClassifier, that automatically classifies the ADA depending on the phenomena that is most probably causing the detected ground motion. ADAClassifier uses auxiliary data, both spatial, e.g. geology, slope, land use, etc, and temporal information stored in the time series of displacement. It can also exploit the ORTO products of the EGMS, which are the horizontal and vertical components derived from the satellite ascending and descending geometries.

Results: In this work we present the first applications and results of the ADATools at national level, starting from the EGMS products.

Conclusions: The tools developed in the RASTOOL project contribute to the distribution of the EGMS products and ease the uptake of its products by non-InSAR experts, giving the opportunity to derive from the EGMS interpreted information over large areas with low human and machine efforts.

EGMS TO SEMI-AUTOMATICALLY IDENTIFY AREAS AFFECTED BY DIFFERENTIAL MOVEMENTS AND DERIVE THE POTENTIAL DAMAGE OF URBAN ELEMENTS EXPOSED TO SLOW-MOVING LANDSLIDES

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Background: Multi-Temporal Synthetic Aperture Radar Interferometry (MTInSAR) is a consolidated technique for detecting and monitoring ground surface displacements. Its application perspective is continuously growing due to the increasing availability of satellite data with free access policy, online-processing platforms, and InSAR products like displacement maps. A clear example of freely accessible InSAR products is the new Copernicus European Ground Motion Service (EGMS), which is providing reliable displacement maps over the whole Europe, based on Sentinel-1 data, with millimetric precision and an annual updating. The EGMS displacement maps include the mean annual velocities and displacement time series starting from 2015, providing line-of-sight displacement data acquired both in ascending and descending geometry, and the derived horizontal and vertical components. This information is strongly valuable for a wide range of users, such as public or governmental institutions, industry, academia, and citizens. Nevertheless, the use and analysis of this huge amount of data is difficult and time consuming, for this reason it is still underexploited. The development of methodologies and tools to automatically extract information, make a preliminary interpretation, and generate operational derived maps, can improve and ease the use of this kind of products.

Purpose: The aim of this work is to present a methodology to identify damage prone areas in urban environments, due to spatial gradients of displacement, starting from wide-area EGMS displacement maps.

Method: The methodology starts from the wide area EGMS displacement map, to focus only on the moving areas through the Active Deformation Areas (ADA) extraction and locally derive the map of the spatial gradients of displacement. The spatial gradients are then used as landslide intensity values to attribute to the exposed buildings a potential damage class. The performances have been evaluated by comparing the results and a field survey-based damage map.

Results: The methodology has been developed over an area of the Municipality of Granada (Spain), in the frame of the RISKCOAST project. Then, it has been applied over a slow-moving landslide located in Andorra, in the frame of the MOMPA project. The proposed methodology is now being implemented as an automated tool to be applied over the EGMS data, in the frame of the ongoing project RASTOOL (EGMS RASTOOL: European ground motion risk assessment tool), co-financed by the EU-Union Civil Protection Mechanism. The results showed good performances in detecting the damage-prone areas. Further, improved performances are expected with the increasing availability of free information regarding building characteristics. The methodology and the first results of the application of the new-developed tool on the EGMS products will be presented.

Conclusions: The proposed methodology constitutes a step forward towards a semi-automatic wide-area slow landslide vulnerability analysis based on the EGMS data, and the derived differential displacements, as intensity information. The output maps can be a valuable support for urban management, ground displacement impact estimation, and damage prevention.

A METHODOLOGY FOR THE ANALYSIS OF A-DINSAR TIME SERIES FOR THE DETECTION OF GROUND DEFORMATION EVENTS: APPLICATION TO SLOW-MOVING LANDSLIDES

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A-DInSAR time series analysis has emerged as an important tool for ground displacement monitoring especially in areas without in-situ monitoring systems and to understand the relation between ground movement processes (slow-moving landslides) and triggering factors (snow, rainfall).

Most of methodologies developed to exploit TS availability are applied to data with at least 12 days or less revisiting time, and they don't identify more than one break point within TS trend, a beginning and ending date of "anomalies" (i.e an occurrence of one or more event(s)) and the total cumulative displacement value.

This work proposes a new statistical methodology to analyse the TS of interferometric data to i) determine the presence of a significant trend in TS; ii) classify the TS trend (linear, non-linear); iii) identify and quantify periods of acceleration (breaks) in non-linear TS providing the beginning and end of the non-linear deformation break(s), duration of the event in days, the cumulated displacement in mm. The methodology was developed and performed in the free software R.

The previous aims are achieved by (i) the Spearman statistical test to determine if displacement and time are related to each other. If they are, i.e. the displacement varies over time, the time series has a trend. If not, the TS trend is uncorrelated. Four methods are proposed to classify the TS trend (ii) based on statistical (Terasvirta and White NN tests) or mathematical-modelling (Pl and PlMa) approaches. To perform iii), the user can set three parameters 1) the number of observations, 2) the minimum velocity threshold, and 3) the minimum cumulated displacement threshold. Outputs are compared with in-situ monitoring systems, meteorological monitoring data (e.g. rainfall, snow height) and already-documented territory events.

The methodology was tested on two Sentinel-1 datasets (2014-2020) covering the Alpine and Apennine sectors of Piemonte region, in northwestern Italy, an area prone to slow-moving slope instabilities.

The methodology was validated at catchment (Pellice-Chisone and Piota basin) and site-specific scales (Brenvetto, Champlas du Col and Casaleggio Boiro landslides) considering areas hit by significant events which determined widespread increase in ground motion and landslides with different kinematics. The comparison with in-situ monitoring instruments and meteorological parameters has shown a good correlation with the event detected by the methodology on TS and with already-collected events in November 2016, in Spring 2018 and in October and November-December 2019. Data provided by the European Ground Motion Service (EGMS) was also considered.

The methodology can be a useful tool to local and regional authorities for risk planning and management of the area both at local and regional scale and it does not require complex computational tools. The methodology applied to Sentinel-1 can provide a new tool for "near-real-time" territory monitoring thanks to shorter revisiting time (6-12 days) with respect to previous satellites. The methodology can be applied to any type of satellite datasets characterized by low or high-temporal resolution of measures and tested in areas with different geological and geomorphological setting to identify and characterised any ground instability (slow-moving landslides, subsidence) at local or regional scale.

GROUND MOTION SENSITIVITY INDEX AS SUPPORTING INFORMATION FOR NATURAL HAZARDS PRACTITIONERS

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The availability of automatic and pre-processed deformation maps from synthetic aperture radar (InSAR) data is rising rapidly. Products like the European Ground Motion Service (EGMS) hold great promise for understanding and monitoring landslides, ground subsidence, volcanic activity, and more. Their interpretation still presents a challenge for many natural hazards practitioners, however, most of which were never trained to work with InSAR data. Simultaneously, the pressure to include these state-of-the-art products in hazard assessments and mapping procedures is increasing. One way to alleviate this problem is by providing well-designed ancillary products that can facilitate the interpretation and understanding of these new datasets. Here we present a set of such datasets generated for the Swiss equivalent of EGMS.

For maximum user-friendliness, the top-level product is a single ground motion sensitivity index (GMSI) map that combines information on radar visibility, measurement sensitivity, and reliability. Sensitivity index maps are useful products to evaluate the feasibility of InSAR-based landslide assessments, but their generation requires both specific expertise and computational resources. Global scale products (e.g., van Natijne et al., 2022) can partly alleviate this need, but their low resolution and reliance on estimated satellite viewing geometries can be limiting in complex alpine terrain. In order to provide a high-resolution dataset adequate for the terrain of the Swiss Alps, we base our GMSI map on a stack of Sentinel-1 SLCs and interferograms from 2018 to 2022 processed at high-resolution and resampled to 10 meters, the baseline resolution of Swiss digital elevation models. The final product combines areas of sub-optimal radar visibility with a single index for landslide sensitivity. This single-layer map is designed to be easy to use for practitioners that have limited or no experience with radar interferometry. For more advanced users, the individual datasets that feed into the GMSI map are additionally provided. This combination ensures a low barrier to entry while providing users with different amounts of expertise with the insight they need.

The GMSI visibility map identifies areas of active and passive shadow, active and passive layover, as well as foreshortening that surpasses a pixel-compression threshold (Cigna et al., 2014). The landslide sensitivity part incorporates both the geometric visibility, as well as the suitability of the ground cover for radar analysis. The former is calculated under the assumption that any displacement follows the general terrain fall line. To assess the ground suitability – and therefore the reliability of measurements – we evaluate the use of interferometric coherence as well as the persistence of scatterers, combining all data from the stack wherever the terrain is snow free at baselines of 12 days, 3 months, and 6 months (of which only the 12-day interferogram is used for the GMSI maps as the best case scenario). The visibility is then weighted by the ground suitability to provide users with just one initial index that summarizes all information. This means that an index in the mid-range could be caused by excellent visibility but bad ground suitability or vice versa, high indices indicate good visibility and ground suitability.

INTEGRATION OF MTINSAR AND POLARIMETRIC TECHNIQUES TO ASSESS CHANGES IN GROUND DEFORMATION TRENDS THROUGH MACHINE LEARNING

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Geological hazards cause every year worldwide casualties as well as significant damages to structures and infrastructures; therefore, their identification and mapping are critical activities for planning land management and risk reduction activities. Particularly in Italy, landslides represent one of the major risks, indeed between 2010 and 2019 more than 13,000 landslide events occurred in Italy and over than 300 in the Tuscany region (central Italy). Monitoring of ground motion events, like landslides, can be carried out through a wide range of approaches, and, in particular in the last years, the use of the MTInSAR (Multi-Temporal Interferometry Synthetic Aperture Radar) techniques has become widespread proving their feasibility to detect a variety of slow-moving phenomena, including landslides, at different scales. In this framework the launch of the European Sentinel-1 constellation has been a turning point. The huge volumes of SAR images with a global coverage and the short revisiting time of the satellite have enabled the development of regional continuous monitoring services. On the other hand, the area of research known as PolInSAR (Polarimetric Interferometric Synthetic Aperture Radar), in which polarimetric and interferometric methods are combined, has received considerable attention but it is mostly applied in other domains (e.g., forest monitoring). Radar polarimetry deals with acquiring, processing, and analysing the changes in polarisation state of the waves induced by the scene, so it allows to extract geophysical information of the targets and to characterize the scattering mechanisms present in the scene.

The aforementioned continuous monitoring system allows to identify trend changes in the time series of displacement, exploiting ground deformation maps, periodically updated. Time series of displacement can be affected by relevant trend variations due to various causes, including landslides. A further step is to benefit from machine learning to assess the spatial probability of deformation trend variations according to the characteristics of the environment and the satellite radar system. In this framework, polarimetry can significantly contribute to improve the results. In fact, this technique has been successfully exploited for different aims, but the most important application concerns land cover classification. Furthermore, one of the most widely used approaches for analysing polarimetric data is based on target decomposition techniques. Therefore, after an initial analysis of the possible contributions of SAR polarimetry, a few polarimetric features have been selected as additional input layers for the machine learning model to achieve spatial probability maps of deformation trend changes caused by landslides. Regarding potential polarimetric features, the focus has been on the output of polarimetric decomposition and on the intensity at different channels, providing a more updated and detailed land cover layer than the commonly used traditional inventories.

The maps of spatial probability of deformation trend changes, resulting from a multidisciplinary approach, if regularly updated, can be an important support for geohazard risk management and mitigation.

MAPPING AND CHARACTERIZING COMPLEX LANDSLIDES THROUGH MORPHOMETRIC AND INTERFEROMETRIC ANALYSIS: THE CASE STUDY OF THE DEBEQUE CANYON LANDSLIDE, COLORADO (USA)

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Purpose: The DeBeque Canyon Landslide (DCL) is one of the many examples of unstable slopes interacting with the highway corridors of the Colorado State (USA) and has been historically considered an area of concern for the Colorado Geological Survey due to its impact on Interstate 70. The landslide can be classified as complex, being kinematically represented by three main interrelated zones characterised by falling (Upper Block), translational and rotational (Rubble Zone and West Disturbed Block failure mechanisms.

The current study focuses on synergically applying high-resolution morphometric analysis and the post-processing of a Persistent Scatterers (PS) interferometric analysis for two main purposes: an accurate delimitation of the ongoing deformation process, and its support in differentiating the spatiotemporal deformative trends, both of which were inadequately assessed by previous literature.

Methods: In the first place, we took advantage of the one-meter resolution LiDAR-based Digital Terrain Model (DTM) to explore the rocky terrain and perform terrain analysis. We used contour lines, and different hillshade maps, along with high-resolution DEM-derivatives (e.g., slope, aspect, Topographic Roughness Index-TRI, Profile, Planar and Total Curvature) to delineate the main landslide characteristics. On the other hand, we characterized the internal deformative pattern and temporal acceleration trends of the measured displacements through an interferometric data post-processing tool, called PS-toolbox and developed by NHAZCA S.r.l., directly in a GIS environment. Decomposed velocity along the horizontal and vertical components, density maps of the displacement and trend changes in acceleration of Sentinel-1 datasets were considered in combination with the high-resolution topographic parameters for refining the geomorphological map of the study area.

Results: Owing to the use and integration of remote sensing data such as PS analysis and morphometric parameters of the terrain, it was possible to delineate the different sectors of the landslide body with a level of detail far superior to that achieved in the literature with field surveys alone. Specifically, the limits of the Upper Block sector, currently representing the highest-risk element considering the road infrastructure crossing the valley floor, were redefined and extended to the west, identifying a broader, retreating deformation process. The Rubble Zone sector, corresponding to most of the landslide body and showing the highest displacement rates (up to 35 mm/year), was internally subdivided into 3 main zones whose boundaries and main movement directions were derived from the interpretation of decomposed velocities and morphometric variables (i.e., curvature and TRI) along several sections along the slope. Moreover, the analysis of temporal trend changes contributed to highlighting three different acceleration phases well correlated with precipitations and snow melting.

Conclusions: The accurate mapping and study of the DeBeque complex landslide were critical for understanding its behaviour and developing a conceptual model of the different failure mechanisms and the respective controlling factors. The insights gained from our study will be relevant for future research aimed at precisely identifying and characterizing complex instability phenomena along highway corridors. Hence, our approach configures as a valuable addition to asset management frameworks.

A PRELIMINARY STUDY ON LARGE LANDSLIDE EARLY WARNING DRIVEN BY SATELLITE INTERFEROMETRY

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China

Purpose: Large landslides often pose a great threat to human life and property. The landslide early warning system is considered an effective way to reduce landslide risk. However, in situ sensor-based landslide monitoring and warning is expensive and unrealistic to be applied to all landslides. Meanwhile, the mainstream deterministic failure time prediction method in landslide warning cannot consider the influence of uncertainty. As a result, it cannot provide decision-makers with reliable landslide warning information, neither sufficient decision-making confidence. This paper attempts to ease the limitations and difficulties faced by traditional in situ sensor-based monitoring and warning, especially to explore the feasibility of solving these problems through spaceborne Interferometric Synthetic Aperture Radar (InSAR).

Methods: First, a large landslide database was established based on literature review and news report. Second, the multi-temporal InSAR (MT-InSAR) was used to obtain the deformation information before the failure of historical landslide cases in a retrospective analysis manner. The feasibility and potential of using MT-InSAR technology for large landslide early warning were assessed from three perspectives: the accessibility of deformation information, the discernibility of acceleration behavior and the abundance of acceleration deformation data. Further, based on the deformation data obtained by MT-InSAR, the classical inverse velocity model was employed together with the sequential Bayesian update theory and the Monte Carlo Markov chain method, to quantify the effects of uncertainties in the deterministic prediction model, and obtain the probability distribution of landslide failure time.

Results:

1. We established a database containing 30 large-scale catastrophic landslides with specific occurrence time records in mainland China from 2016-2021.
2. Through the MT-InSAR technique supported by Sentinel-1 satellite data, the deformation information of 28 landslides (about 93.33%) before failure can be obtained, and the acceleration behavior of 11 landslides (about 36.67%) before failure can be identified. More importantly, deformation data in acceleration phase before failure for eight landslides (about 26.67%) can be used for failure time prediction.
3. The predicted failure time confidence interval can reasonably cover the observed landslide failure time, thus validating our proposed method.

Conclusions:

1. We demonstrated the feasibility of spaceborne InSAR measurement technology for large landslide monitoring and early warning. Although its success rate was only 26.67% by far, we consider it has a good potential in future InSAR-based large landslide early warning.
2. The revisiting period of satellites is the main limitation factor, but it will be effectively alleviated in the future.
3. A probabilistic prediction method of landslide failure time that can quantify the influence of uncertainties was proposed, thus providing a valuable reference for large landslide early warning.
4. The proposed method improves the existing large landslide early warning system from the perspective of earth observation, which is expected to mitigate the risk of large landslides.

INTEGRATION OF SATELLITE SAR AND OPTICAL ACQUISITIONS FOR THE CHARACTERIZATION OF THE LAKE SAREZ LANDSLIDES IN TAJIKISTAN

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Purpose: Around 1300 lakes make up Tajikistan, which is situated where the Euro-Asian and Indian tectonic plates intersect, and the majority of these were formed by rockfalls and collapsing moraine deposits. Moreover, the area is susceptible to powerful earthquakes due to its localisation. In 1911 a big earthquake in the area generated the Usoi dam, which consequently led to the creation of Lake Sarez, in the Easter side of the country. The region is dominated by high snow-covered mountains, and this complicated topography makes difficult to reach and work in it. So, due to this inaccessibility remote sensing plays an important role in risk assessment and monitoring of the region. The purpose of this work is to provide a detailed overview of ground deformation of the area of Lake Sarez using both the Interferometric Synthetic Aperture Radar (InSAR) technique and optical analysis, with a specific focus on both the right bank and left bank side landslides that affect and threaten the lake.

Methods: To study and analyse the two landslides, an integrated satellite analysis has been applied with the aim to collect as much information as possible about the slope instability phenomena of the area of interest. In particular, remote sensing practices such as InSAR using the Sentinel-1, processed through the SqueeSAR approach, and an optical image correlation using COSI-Corr technique applied to SPOT-6 and SPOT-7 acquisitions have been used. In this way, a synoptic and complete analysis of the ongoing displacements was retrieved, allowing to reconstruct the temporal evolution and to solve the spatial variability of the deformation affecting the Lake Sarez banks.

Results: The InSAR data cover the period between 2016 and 2020, and the optical images have been chosen between 2015 and 2021. The two methods emphasize movement and displacement in both right-bank and left-bank landslide, and they concur on the definition of the broader kinematic picture of landslides that doesn't seem to have significant acceleration during the monitored period. The optical method shows the movement especially in the left-side bank landslide. In addition, since the volume of the right-bank landslide is still widely debated (estimated volume around $1.4 \cdot 109$ m^3 and area 5.34 km^2), InSAR data have been also used to develop a model of the geometry and the depth of the sliding surface of a potential landslide that could occur and cause a huge wave that could top over the dam and create a destructive flood downstream. Data shows that most of the movement is located in the central part of the body.

Conclusions: The multi-perspective analysis performed has provided interesting results on the displacement and movement of the two landslides and it may represent a solid base and a starting point for modelling the mechanism of the landslides and also for the evaluation, reduction and mitigation of geohazard risks, especially in impervious areas.

SEQUENTIAL SBAS-INSAR BACKWARD ESTIMATION OF HISTORICAL LANDSLIDE DEFORMATION TIME SERIES

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Purpose: In most cases of landslide deformation monitoring, we can obtain the deformation time series with SBAS InSAR technique for a certain period of time. If it is unstable, it is necessary to recover the previous deformation to reveal the initial time. Generally, we will process all SAR images including ones processed at the first time, which makes InSAR processing time-consuming and heavy computer burden. Therefore, we propose the sequential SBAS-InSAR backward estimation to recover the historical deformation time series, which is flexible and quickly to recover early deformation time series upon request.

Methods: Firstly, the deformation time series for a certain period of time is obtained through SBAS-InSAR technology. Then the historical deformation time series is recovered dynamically and quickly based on the historical unwrapped interferograms using backward sequential adjustment. In theory, new algorithm is equivalent to the traditional SBAS-InSAR method.

Results: Firstly, we simulate the deformation time series with three different deformation models, that is, linear model, trigonometric model, and quadratic model (Figure 1). In real case, 44 unwrapped interferograms generated from 19 TerraSAR images over Heifangtai region, Gansu Province, China, are used for the landslide deformation time series estimation. Compared with SBAS-InSAR, sequential SBAS-InSAR backward estimation can get similar results, but be much more efficient and save computer storage significantly. Lastly, in-situ GNSS time series results verified the results from new proposed method (Figure 2).

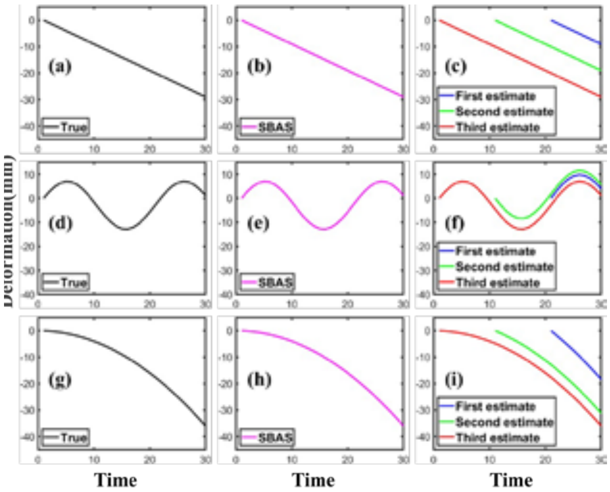

Fig. 1: Simulated results of three different deformation models, i.e., linear model, trigonometric model and quadratic model. (a), (d) and (g) are simulated deformation time series, (b), (e) and (h) are estimated results of SBAS-InSAR, (c), (f) and (i) are estimated results of sequential SBAS-InSAR backward estimation, respectively.

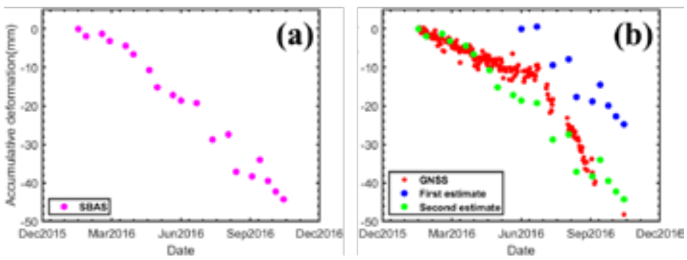

Fig. 2: Deformation time series of a typical point estimated by SBAS-InSAR and sequential SBAS-InSAR backward estimation based on 19 TerraSAR-X images over Heifangtai region, Gansu Province, China, (a) the result of SBAS-InSAR time series, (b) the sequential SBAS-InSAR backward estimation time series and GNSS measurements.

Conclusions: The sequential SBAS backward estimation results are consistent with those of SBAS-InSAR method. In terms of recovering historical deformation time series, the new method has higher processing efficiency and less computer storage requirement.

6th WORLD LANDSLIDE FORUM
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TYPICAL LANDSLIDES DEFORMATION RESPONCES TO CLIMATIC DISTURBANCE IN PAMIR AND QINGHAI-TIBET PLATEAU USING SATELLITE INTERFEROMETRIC SAR

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Purpose: The negative impact of climate change on landslides was reported in the Arctic, Euro Alps, Canada, and Alaska. However, landslide cases related to Pamir and Qinghai-Tibet Mountain were still scarce. Meteorological and reanalysis data evidenced that both two regions have experienced continuously increasing temperatures and anomalous weather events, which also caused slope instabilities that could generate risks for the mountain territories. Considering two regions dominated by different climatic conditions, landslide types, and deformation processes were assumed differently. Our work aimed to highlight the landslide deformation process and reveal the deformation response in different climatic conditions. For example, the apparent instability phenomenon in Pamir was the rock glacier surge, which quickly formed glacier lakes and triggered unpredicted lake outbursts. Another conspicuous phenomenon was the acceleration of the solifluction rate in Qinghai Tibet, which destroyed the grassland and break the equilibrium of permafrost.

Methods: In our study, we utilized satellite-based interferometric monitoring to retrieve ground motion and identify landslides and rock glaciers based on the deformation characteristics. Deformation evolutional scenarios of typical cases were reconstructed by combining InSAR and Long time-series Offset-tracking methods, accommodating a full spectrum of rock glacier or massive landslide deformation processes from creeping to fast flowing.

Results: 1) Potential solifluction identification in Qinghai-Tibet Plateau.

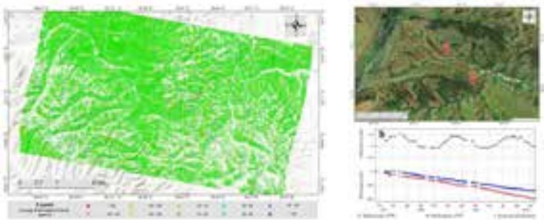

Fig.1: Regional solifluction identification using Improved InSAR technology (left one) b the enlarged area of black rectangle indicating the potential solifluction with The deformation characteristic have seasonal oscillation and fast creep two components.

2) Potential rock glacier identification in Pamir Plateau.

Fig. 2: Regional rock glacier identification using InSAR technology where bear 20 rock glaciers were detected near China-Pakistan Highway in Pamir.

3) Deformation precursory of typical solifluction in Qinghai-Tibet Plateau.

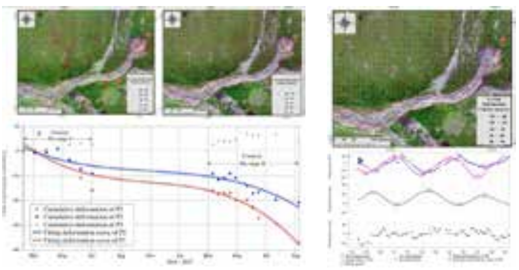

Fig. 3: Typical solifluction in Yunshu, Qinghai-Tibet Plateau from creeping at the re-failure stage to the seasonal oscillation at the post-failure stage.

4) Deformation of a typical rock glacier in the Pamir Plateau. - 5) Deformation evolutional scenarios were reconstructed using the long time-series Offset-tracking (LTOT) method in case of large-magnitude deformation.

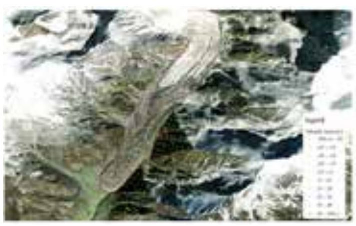

Fig. 4: Typical deformation of a rock glacier in Gongur, Pamir Plateau was represented.

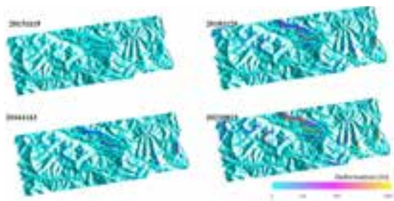

Fig. 5: Deformation scenarios were reconstructed and crucial evolutional stages were classified.

Conclusions: Through our research, we have obtained the following points: 1) different landslide types were identified in Pamir and Qinghai-Tibet Plateau. 2) Deformation characteristics related to the climatic environment were analyzed and compared in-depth. 3) In terms of the different deformation processes, monitoring approaches or strategies were discussed.

SESSION 1.4

LANDSLIDES AND SOCIETY: CULTURAL, EDUCATIONAL, ETHICAL, AND SOCIAL ASPECTS IN SUSTAINABLE LANDSLIDE RISK REDUCTION (part II)

LOCALLY LED LANDSLIDE RISK REDUCTION: EXPERIENCES AND LESSONS LEARNED FROM HILLY AREAS OF NEPAL

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Purpose: The paper aims to share field-based evidences on what drives community perceptions for landslide risk reduction, as well as communities' willingness to work on landslide mitigation and relocation in the context of Nepal. This way it aims to contribute to discussions about locational decisions of human activities and the actions taken to reduce the landslide risks in a sustainable perspective. People in Need (PIN) Nepal together with the communities, stakeholders from Government of Nepal and in collaboration with academia implements programme entitled "Pratibaddha 2: Together for Disaster Preparedness and Early Action in Vulnerable Hill Areas of Nepal". This programme focuses on four landslide-prone municipalities in Nepal. Specifically, in monsoon of 2023 (June-October), PIN Nepal aims to pilot and contextualize locally led early action, landslide mitigation, and relocation based on detailed understanding of hazard, exposure and vulnerability while addressing the specific needs of different vulnerable groups.

Methods: Central to DG ECHO funded Pratibaddha 2 programme is bridging the science and policy into community practices. The programme has simplified the scientific knowledge of landslide exposure in a concept understood by the local government and indigenous people, while integrating local knowledge on landslides. Experience of PIN Nepal in landslide prone areas for more than 7 years shows that people's perception of risk is shaped by locational culture, socio-economic conditions, access of resources, social capital, livelihood challenges, among others. Current early action and landslide mitigation program has been designed going beyond these locational aspects adopting people-centered approach and citizen science encompassing psychological and behavioral aspects of at-risk community. Therefore, the activities are aligned to embed landslide mitigation and early action that is not too foreign for the community but can be embedded into their current practice as incremental success for risk reduction, for saving lives and livelihood. Our approach has been on "Living with Landslides", understand people's perceptions of risk and how these perceptions drive behavioral decisions about adaptive measures. This entails working with existing governmental systems rather than siloed approach and unlocking government funds, along with geohazard categorization and integration with cascading hazard approach through remote sensing. Focus has been on the sustainability of the model at the local level, rather than on scientific or technological solutions, to reach adequate responsibility sharing between communities, governments, scientists and practitioners.

Results: During the session the evidence from monsoon 2023 will be shared with the aim to inform the science-practice discourse on landslide risk reduction under following areas, such as landslide exposure through geohazard assessment, early warning-early action, risk communication on the basis of specific needs, locally led nature-based solution and leveraging social protection.

Conclusions: The paper will aim to contribute to inform the existing theoretical debates and narrowing the gap between technical and engineering advancements in the landslide knowledge, scientific definitions and perceptions of landslide risk, on one hand, and the perceptions, ability and willingness of the exposed communities to effectively reduce landslide risk, on the other.

IMPROVING LANDSLIDE RISK ASSESSMENT AND RISK PERCEPTION FOR THE PRIORITISATION OF MITIGATION MEASURES AT REGIONAL LEVEL - THE EXPERIENCE OF LOMBARDY (ITALY)

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Purpose: It is generally accepted that, when aiming at preventing natural disasters, the prioritization of mitigating measures and the allocation of public spending should be informed by a risk-minimization approach constrained by the finite amount of available resources. However, although risk-based decision making may be conceptually simple, its practical implementation faces many challenges. This paper examines the difficulties in comparing risk estimates regarding different types of landslides and in comparing landslide risk with the risk from "competing" hazardous phenomena (like flooding). It then proposes strategies to refine the risk perception of key decision-makers in charge of resources allocation and to facilitate the dialogue with the various stakeholders.

Methods: Starting from the experience of geological and hydrological risk reduction programmes implemented by Regione Lombardia (Italy) in the last three years, the interplay of explicit and implicit risk quantifications is dissected and the risk reduction role of the regional government of Lombardy (approximate area 24'000 km2, population more than 10 MM people, GDP about 400 B€) is examined within the wider national context of Italy (approximate area 300'000 km2, population almost 59 MM people, GDP about 2'000 B$). The role of the regional government in harmonizing large scale inter-regional planning and small-scale needs, highlighted by local authorities, is also given consideration.

Results: A systematic review of the current procedures against risk management theory and best practices highlights a few opportunities to improve the prioritisation of public spending. Some of these improvements are difficult to implement (e.g. increased frequency of inter-regional planning documents reviews) and should be treated as long term aspirations. Some other are simpler, like the strategic use of local sub-catchment studies or the categorisation of potential events in hazard classes and impact classes more closely related to the specificity of landslides, rather than generically extended from hydrological and meteorological processes. These easier-to-implement changes should be immediately pursued and championed as they can contribute to from a more accurate risk perception and to achieve a better alignment between decision makers and stakeholders. In the discussion, care is taken to distinguish between the elements that are intrinsically linked to the case history considered here and the elements that have general validity and can be legitimately extended to other contexts in the realm of landslide risk mitigation.

Conclusions: A more explicit quantification of risks to life, to the built environment and to the economy, as well as an effort to also quantify the uncertainty associated with the risk estimates, has the potential to add robustness, rigour, and transparency to the prioritisation of public spending for landslide risk reduction. It can also provide a framework to support the delicate undertaking of risk communication between technical experts, public officers, and the wider citizens community.

INTEGRATION OF LOCAL INDIGENOUS KNOWLEDGE IN DISASTER RISK REDUCTION MEASURES: OPPORTUNITIES, CHALLENGES AND PERSPECTIVES

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Purpose: In the recent decades, academics and the international community have increasingly recognized the potential contribution of local indigenous knowledge (LIK) to understanding and managing the environment. While some work has been done to raise awareness of LIK and indigenous practices through survival stories, researchers and practitioners agree that the process of integrating LIK and practices is not being done fully and effectively. The purpose of this study is to raise awareness of the importance of LIK and to contribute to the development of an action plan for collaboration among different stakeholders in disaster risk reduction (DRR) and sustainable development (SD).

Methods: In order to advance towards the integration of LIK in DRR, the study was first conducted through an extensive literature review of successful practices and the process of integrating LIK into DRR around the world. Several relevant stakeholders involved in LIK and DRR from different parts of the world were then interviewed. The core questions were related to the challenges, opportunities, and limitations of the integration process of LIK into DRR measures. To achieve a successful discussion, the semi-structured interviews were conducted in two phases. The first phase consisted of a pilot interview followed by feedback on the interview questions. Based on the results of the feedback, the questions could then be reworded or rephrased in a second interview phase. At the end, an appropriate synthesis and analysis was conducted to identify key aspects and commitments that could contribute to the formulation of an action plan for integrating LIK into DRR.

Results: It is fundamental to keep working on the integration of LIK into DRR to overcome current challenges. The literature review and interviews were useful tools to identify key aspects of this process. The integration of LIK can provide multiple benefits to communities, researchers, practitioners, and government agencies. The discussion revealed several key elements essential to LIK integration, such as: Education, Self-Determination, Advocacy, Policy, Effective Participation, Partnership, Impact and Monitoring. These aspects are illustrated by successful case studies found during the literature review. It was also possible to identify the differentiated and shared responsibilities that each stakeholder involved should take on to advance in the protection and integration of LIK into DRR.

Conclusions: There is ample evidence of the role of LIK and practices in disaster preparedness, response, and recovery. Moreover, integrating LIK into DRR can be an important key to successful risk management, as it leads to more sustainable and cost-effective outcomes. Integrating LIK can promote community participation and ownership by inspiring the community to implement innovative strategies to mitigate and to adapt to natural hazards. The current challenges we face, such as global change and compounding impacts, call us to build local alliances between civil society, indigenous collectives, disaster risk reduction institutions, and the private sector. Each stakeholder has a role to play in disaster preparedness and prevention. Therefore, it is important to value LIK and implement innovative strategies to engage indigenous and local communities in disaster risk reduction plans, policies, and actions.

A COLLABORATIVE APPROACH FOR THE COLLECTION OF VULNERABILITY INDICATORS TO LANDSLIDE HAZARD

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Purpose: This work stems from the collaboration between CNR-IRPI and an Italian municipality in the framework of geo-hydrological risk reduction activities. The collaboration was aimed at monitoring building characteristics using specific vulnerability indicators to implement local emergency civil protection plan.

Methods: The data gathering was carried out through an easy, and affordable web-apps able to collect, characterize, and analyze buildings characteristics and their surroundings exposed to geohydrological events, in rural and in urban contexts. We conceptualized and designed a digital survey-form designed to be compiled through mobile Apps specifically developed for Android and iOS environments. The data collection, was carried out through the active participation of citizens, municipal technicians, civil protection volunteers, professionals and researchers which were comprehensively identified as “Sentinelle del territorio”. The experts’ viewpoint was discussed with volunteers, who deal with the residents on a daily basis and understand their perspectives, raising practical questions which proved fundamental for the management of the data collection phase. The complex work behind the survey form conceptualization, aimed at promoting a wide usability, benefited from the collaboration of different subjects. The filled-in forms complied by the sentinels during the survey, were automatically sent to a dedicated server supporting data, coordinates, and media files.

Results: A total of 530 survey forms in landslide-susceptible areas were compiled in a few months. To reach these results, a group of 25 people made up of volunteers, professional technicians, researchers and municipal technicians have worked together actively. The use of the digital survey forms made it possible to immediately have a large amount of data available. The data were stored in two separate databases, one for the ODK, supported on a server managed in-house by the IRPI (used for Android smartphones), and one for the GIS Cloud, managed by the iOS Cloud (used for iPhones), that were merged together.

Conclusions: The methodology offered the opportunity to monitor building characteristics and vulnerability through the active participation of residents, municipal technicians, civil protection volunteers, and researchers, thereby increasing the awareness on the geo-hydrological hazards and buildings vulnerability. The proposed public participation method for data-gathering increased the knowledge across residents providing a better understanding of the urban systems, of the buildings condition and exposure in relation respect to the geo-hydrological risk. The method can be considered as part of the decision support systems for civil protection. The application of mobile technology for data collection can be effectively used when local government resources are limited.

LANDSLIDES AS A HIGHER EDUCATION TOPIC AND BEYOND

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Purpose: A review on higher education study programmes and open-access educational material on landslides as natural hazards and on landslide disaster risk reduction for dissemination of the results to world landslide community.

Methods: Web survey of the relevant web databases and search engines for higher education study programmes and other educational materials related to landslide disaster risk reduction.

Results: Results of the study will be submitted in March 2023 as an original article to P-LRT book: Mikoš, M. (2023). Landslides in Higher Education Curricula and Beyond. In: Progress in Landslide Research and Technology, Volume 2 Issue 2, 2023. Progress in Landslide Research and Technology. Springer, Cham. 12p.

Conclusions: The importance of education for landslide disaster risk reduction is clear and unequivocal. The education for natural disaster risk reduction should start as early as possible, even in kindergarten (pre-school) level, and should be offered as a life-long education topic for wider society. The topic of landslide disaster risk reduction in all of its variety and depth, comes to full coverage in the curricula of higher education institutions. This topic is widely covered in undergraduate and graduate study programmes in engineering (geotechnical engineering, geological engineering, civil engineering, …), but also in science programmes (geology, geography, …) and social sciences programmes (risk management, disaster management, resilience, risk dialogue …). The topic is mainly covered as a constituent part of more general courses, and to a lesser extent as courses on slope stability and landslides. This is why summer schools on landslide disaster risk reduction are to be welcome to offer students an opportunity to deepen their understanding and knowledge in this topic, coming from a variety of disciplines. They make it possible to have an inter-disciplinary milieux, and to stimulate cross-sectoral thinking that is important to understand landslides as socio-technical complex system that needs cross-sectoral approach and systems thinking, quite often supported by critical and innovative thinking. The article gives a short overview of some (selected) courses and study programmes worldwide offering knowledge and competencies for landslide disaster risk reduction. There are though many more higher education study programmes not covered in this overview, as there are thousands of universities around the world. With respect to summer schools on landslides, the overview is more complete, as the offer is not so extensive. The worldwide landslide community is invited to support efforts for society resilience against landslides by intensifying their efforts for capacity building in parallel to their research activities. For the International Consortium on Landslides, the KLC 2020 Commitment for Global Promotion of Understanding and Reducing Landslide Disaster Risk, is a standing support and reminder to be active (also) in the field of capacity building, not only through research, but also education. The ICL activities, not only in research, but also in capacity building for society resilience, is supporting the implementation of the ninth phase of the UNESCO Intergovernmental Hydrological Programme (IHP-IX) 2022-2029.

"ACQUA VIVA (ALIVE WATER): THE SMART CITIZENS' NUDGE" TO ACT ON BEHAVIOURS TO WATER-RELATED DISASTER RISK REDUCTION

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Purpose: Citizens play a decisive role in the success of territorial policies. Without their response and in the absence of responsible behaviour the positive outcome of government choices remains limited. "Nudging" is a gentle boost to help people choose what is best for themselves and Society, allowing the harmonization of individual behaviours without forcing anyone. INGV researchers promote the LifeLong Learning training process on the importance of proper behavior in natural risk reduction and the hackathon by EPALE (Electronic Platform for Adult Learning in Europe) was a special occasion to favor knowledge, awareness, how to act, self-protection and prevention on these issues. Indeed, the team “Smart citizens” from the Provincial Center for Adult Education (CPIA) of la Spezia was selected to take part in the EPALE EDU HACK 2022 competition, titled “Making peace with the Environment. Territorial proposals for digital innovation for green transition. CPIA teacher and INGV researcher designed with their team the nudge “Acqua Viva (Alive Water): the Smart Citizens’ nudge” to achieve sustainability, environment respect and water-related disaster risk reduction.

Methods: The product is inspired by behavioural economics to improve the impact of individual actions in countering the problem of land fragility, from the perspective of hydrogeological disruption. The experience of Salvina’s games series, widely spread during the pandemic, was the starting point for the nudge gamification. In particular, Salvina and the Flood, Salvina and the Environment, and Salvina and the 4Rs games (Piangiamore and Maramai, 2022) were reworked to focus on the theme of water as a natural resource and valuable asset for the Ligurian landscape defence. The nudge considers the multi-ethnic context and cultural differences by using videos, images and the support of a glossary to enhance learning through educational play.

Results: The final product applied innovative digital techniques through the Challenge Based Learning didactic-collaborative approach, focusing on the importance of the proper maintenance of the territory from the hydrogeological point of view. The final works of the competing teams were displayed to the jury. Acqua Viva won the special "Social award” as the most voted nudge by the Facebook audience and placed fourth in the EPALE hackathon.

Conclusions: Special attention has been devoted to safe behaviours to adopt in case of landslides and floods in support of Civil Protection activity. Moreover, all the digital products correlated to the nudge also have the Transformative Learning purpose on the sustainable use of water through small daily actions: people should reflect on right individual choices that are best for the whole community. The Aqua Viva nudge will be shared in a special online event during the World Water Day 2023, where all schools in Italy are invited to race. The online challenge will be an educational chance to encourage behaviour change and to "nudge" citizens choosing a path toward collective well-being.

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GEOMORPHOLOGY IS A GAME: EXPLOITING THE CAPABILITIES OF GAME ENGINES FOR IMMERSIVE LANDSLIDE EXPERIENCES

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Scope & Objectives: Computer simulations in landslide science strongly rely on standalone software packages with clearly defined fields of application, mainly to inform risk management. Important features of modern landslide risk management consist in the active involvement of potentially affected communities, and in broad-scale awareness-building, e.g., in public education. This leads to an increasing need to communicate model results in an expressive way. Game Engines (GE) are specifically dedicated to the creation of captivating, visual experiences distributed to a wide range of consumers for profit. The performance of the underlying software is built on long-term advancements facilitated by community driven development and the vast resources of the entertainment industry. The result are sophisticated, modular software frameworks ready to be used freely for nonprofit purposes. There is potential for gamification in geomorphological research by developing approaches to complement traditional data processing and visualization with immersive experience, embedding the Unreal 5 GE (UR5) on several levels. We identify the following starting points:

1. Gamifying science communication to enhance knowledge transfer: UR5 facilitates the straightforward creation of realistic, immersive, virtual reality (VR) environments. VR experiences of precomputed landslide scenarios allow players to explore their surroundings and interact with the environment. This promotes imparting knowledge in a joyful way.
2. Gamifying process simulation to empower knowledge production: to support immersive, naturalistic depiction UR5 simulates spatially distributed system dynamics. Inbuilt software development kits contain programming logic implementing robust physics in a computationally efficient way. This is the basis for the application in the context of landslide science.

Methods & Results: A key to the implementation of (1) consists in the improvement of the interoperability between state-of-the-art simulation tools and UR5. Outputs of the open-source mass flow simulation tool r.avaflow already come along with Python scrips allowing for the subsequent, automatic import of static meshes in UR5. We are working on case studies of historic giant landslides in the Austrian Alps (to be experienced at the visitor centres of the relevant UNESCO Global Geoparks) and in oceanic island environments. We aim to enhance player-simulation synergies by allowing the triggering of landslides, object interplay and storylines conveying process understanding. One particular challenge consists in the implementation of flow-type landslide repercussions on players within the object-oriented framework of UR5. Video games and cinematic animations rely on GEs high performance in simulating realistic movement, collision, and damage. This implies their ability to mimic the laws of physics and certain material properties making them auspicious for scientific simulation. The UR5 framework is designed for discrete object interaction. Thus, previous studies suggest the eligibility for rockfall simulation as proof-of-concept for (2). We want to address and tackle the known core challenges of fragmentation behavior and output evaluation.

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SESSION 5.5

ADVANCES IN EARTHQUAKE-INDUCED LANDSLIDE RESEARCH (part II)

REGRESSION ANALYSIS FOR DEVELOPING EMPIRICAL FORMULATION FOR ESTIMATION OF CO-SEISMIC LANDSLIDES CONSIDERING DIFFERENT CHARACTERISTICS OF GROUND MOTIONS

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Purpose: Many large and moderate-magnitude earthquakes cause the activation of new and old landslides, which accounts for a significant portion of the total damage caused by the earthquake. Slope instability is among the most common, destructive, and dangerous phenomena affiliated with any seismic hazard, especially in mountainous regions. Therefore, estimation of co-seismic displacement of slopes is critical for taking proper preventive measures and designing and engineering slopes to avoid slope movement or reduce the harm caused by the earthquake or associated landslide. Existing research provides empirical relations for co-seismic displacement calculation considering several ground motions' peak ground acceleration (PGA). However, it is evident that for any ground motion, several other parameters such as duration, Arias Intensity, peak ground displacement, and velocity are also very significant in causing co-seismic displacement. Therefore, this study attempts to modify the existing empirical relation by examining all the above-mentioned parameters of different ground motions

Methods: Work methodology includes the selection of ground motions, different slope profiles with distinct strength properties (Shear modulus, density, and void ratio), and displacement computation for all considered slope profiles. Also, for seismic component whole acceleration time history of 40 different ground motion spectrum are considered. The ground motions included in the study are scaled according to the target design spectrum specified in the IS 1983 (Part 1): 2016- Indian Code. Subsequently, the displacement of all considered slope geometries under different seismic ground motions is calculated by numerical simulation using the GeoStudio 2022 software package and by the existing empirical formula. After that, the comparison of computed co-seismic displacement of slopes is carried out, which shows that the existing empirical relation misses the predicted result by a significant margin.

Results: This study finds a correlation between co-seismic displacement and the different characteristics of ground motion, recognizing the dominant ground motion characteristics that affect co-seismic displacement. After that, the existing empirical relation is modified by regression analysis, conferring to the dominant ground motion parameters. The empirical relationship derived from the regression analysis is applied to calculate the displacement of several real-life landslide scenarios. These scenarios are also modeled using advanced FEM analysis. The resulting co-seismic displacement computed from the developed empirical relationship is found to be highly consistent with the results obtained from the FEM analysis.

Conclusions: The proposed empirical formula is reliable with the real field scenario and considers the different characteristics of an earthquake. Hence, it can be used by engineers and planners for further sustainable development of slopes and by state authorities for proper mitigation measures of vulnerable slopes.

Keywords: Co-seismic displacement, Ground motion characteristics, Regression Analysis

PREDICTIVE MODEL OF REGIONAL COSEISMIC LANDSLIDES'S PERMANENT DISPLACEMENT CONSIDERING UNCERTAINTY

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Purpose: Being a widely adopted method for coseismic landslide rapid assessment, the Newmark sliding block model is limited by uncertainties from slope material (e.g., shear strength, pore water pressure, and block thickness), especially in regional-scale assessment. This study focuses on the uncertainty involved in the Newmark model and develops a novel framework.

Methods: The proposed framework consists of two optional uncertainty assessment methods, Monte Carlo (MCS), Logic tree (LTS), and seven optional regression functions for predicting regional coseismic landslides' permanent displacement. Compared with the existing methods, the proposed framework is argument-driven, avoiding a huge number of repetitive simulations. The meizoseismal area struck by the Jiuzhaigou earthquake, in China, is considered as an illustrative example to compare different regression functions by instantiating fourteen predictive models based on this framework.

Results: The results indicate that using LTS, with a specific regression function, leads to better prediction compared to MCS. The predictive performance varies depending on the regression function used, while the overall performance of the function using arias intensity superior to that using the peak ground acceleration.

Conclusions: The proposed framework can provide a meaningful measure for making informed decisions to diminish the potential risk of earthquake-induced landslides, and/or generating emergency strategies to mitigate post-earthquake consequences. It is worth noting that the application of the proposed method for deposits where the soil strength parameter values do not fit the normal distribution may be limited as only normal distribution for soil strengths is considered in this study.

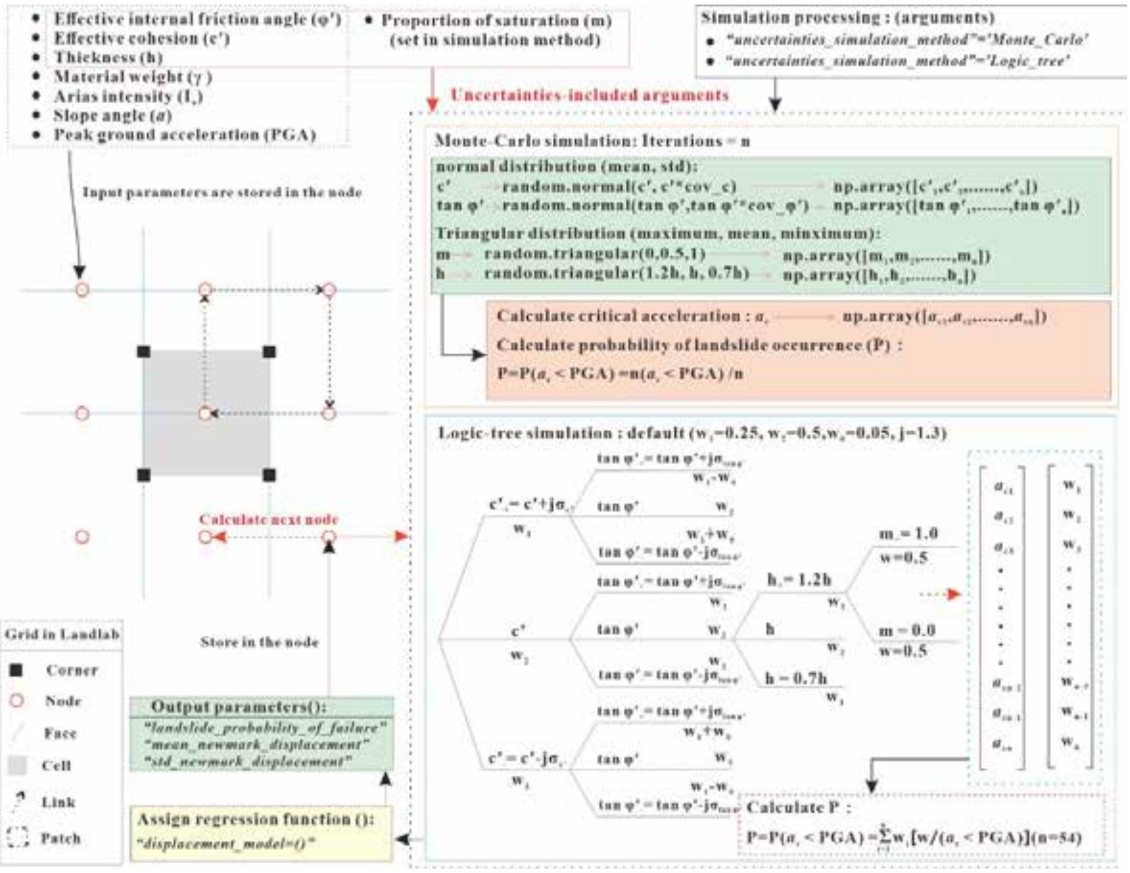

Fig. 1: The proposed framework in this study. (left-hand side shows a set of primitive elements in the Landlab).

USING LONGITUDINAL MODELS FOR POST-SEISMIC LANDSLIDES PREDICTION IN NEW ZEALAND

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Purpose: Post-seismic landslides are a long-term effect of earthquakes that increase the risk of cascading disasters. Predicting these post-seismic landslides can decrease the hazard caused by these landslides that can otherwise cause large scale destruction. Modeling these landslides have been attempted in the literature using various techniques. Major types of models used are physical, statistical and geomorphological by nature (Reichenbach et al. 2018). The majority of statistical methods for susceptibility mapping proposed in literature use cross-sectional analysis that lose the temporal link in multi-temporal inventories. On the other hand, longitudinal analysis has been applied far less frequently for susceptibility mapping of post-seismic landslides. While such longitudinal models are frequently employed in other domains of geoscience, their relative performance in performing landslides is not well understood. In particular, the use of time-varying covariates such as rainfall data and the Normalized Difference Vegetation Index (NDVI) might lead to more accurate predictions of the risk for landslides (Reichenbach et al. 2018).

Methods: In this work we compare existing cross-sectional models with longitudinal models using data from the 2016 Kaikoura earthquake. This earthquake occurred in the southern island of New Zealand and triggered more than 25000 landslides (Tanyaş et al. 2022). These landslides were retriggered in the following years and there are multi-temporal landslide inventories that capture their evolution. The inventory was mapped by automatic techniques proposed in the literature containing landslides in the years 2016 to 2021 after the earthquake (Bhuyan et al. 2023). We generated slope units for the study region and extracted covariates related to the geological, hydrological, morphological and seismic properties.

Results: For evaluating each susceptibility model, we calculate sensitivity, specificity, the confusion matrix, Kappa coefficient, ACC, and AUC from tenfold cross validation. Further, we experiment with oversampling to better balance the two types of error rates. Our preliminary results indicate that longitudinal models can significantly improve the predictions of post-seismic landslides compared to other commonly used cross-sectional methods.

Conclusions: Longitudinal models can help in improving the temporal aspect of Landslide susceptibility in assessing and estimating the hazard due to post-seismic landslides.

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DYNAMIC MODELLING OF SEISMIC WAVES AND SLOPE INTERACTION TO INFER EARTHQUAKE-INDUCED LANDSLIDE DISPLACEMENTS FOR MULTIHAZARD-SCENARIOS RENSTITUTIONS

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Purpose: The prediction of landslides (re)-activated by earthquakes is a key point in the evaluation of the multi-risk associated with the occurrence of seismic events in high seismicity areas. Nowadays, co-seismic displacements in landslides are usually assessed at regional scale by approaches exploiting implementations of the Newmark's method (1965) on GIS. Nonetheless, due to the effects related to the seismic waves-landslide mass interaction, the predicted displacements are not always reliable. To account for these effects, the propagation of seismic solicitations into landsliding slopes should be modelled through more complex methods such as numerical tools that, however, require expertise and too long computation times to be performed at regional scale for a large number of case studies. This work aims at evaluating the reliability of the regional scale previsions provided with the Newmark's method – based approaches through multi-parametric stress-strain analyses performed at the slope scale. More in particular, the objective of this study is to understand under which conditions the Newmark method gives significantly different displacements than the numerical stress-strain analysis. Then, for those conditions and consequently for the associated considered cases, we want to quantify the associated relative error between both predictions.

Methods: 216 among purely translational and rotational landslide models were generated by combining morphometric (depth/length ratio of the landslide), topographic (slope angle) and geotechnical parameters with 3 different volume classes. The aforementioned parameters were deduced by statistical analyses on available worldwide landslide databases (Domej & Pluta, 2023; Martino et al., 2019 and Tanyas et al., 2019). In that manner, the deduced models can be considered representative of real landslides in terms of failure mechanism, geometry and geotechnical characterization. The 216 simplified models were dynamically solicited by the FDM calculation code FLAC 8.0 (Itasca) with 17 equivalent signals (LEMA_DES approach, Lenti & Martino, 2010) characterized by a mean period between 0.08 s and 2 s and an Arias Intensity in the order of magnitude of 0.1 m/s.

Results: The outputs of the stress-strain analysis in terms of relative horizontal displacements of the center of mass of the modelled landslides were compared to the respective Newmark's displacements computed by the empirical equation proposed by Hsieh et al., (2011).

Conclusions: The multi-parametric analysis allowed investigating the role of the introduced variables (landslide size, inclination of the slope, geotechnical composition, failure mechanism and frequency of the input) on landslide mobility. Finally, comparison with Newmark's displacements demonstrated that outputs from the two different approaches can differ, highlighting the necessity to do a step further on the topic of the evaluation of the hazard related to landslides triggered by earthquakes.

MECHANISMS AND PREDICTION OF EARTHQUAKE AND CLIMATE CHANGE-INDUCE CASCADING HAZARDS

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Purpose: Strong earthquakes and climate change-caused extreme weather events in steep orogens can induce cascading chains of surface processes that have short- to long- term impacts on landscape. For earthquake-induced cascading hazards, the chain initiates from the coseismic landslides that can generate enormous quantities of debris over vast areas. The occurrence of coseismic landsides is controlled by the coupling effects of geomorphological, geological, hydrological and seismotectonic factors. The distribution of steep slopes and high shaking intensities can explain, to first approximation, the areas and volumes, and the spread of coseismic landslide locations.

Methods: The model can predict the spatial distribution probability (susceptibility) of coseismic landslides within a few minutes after receiving seismic factors. Thus it has been used for emergency response of several large earthquakes in China.

Results: The model can predict the spatial distribution probability (susceptibility) of coseismic landslides within a few minutes after receiving seismic factors. Thus it has been used for emergency response of several large earthquakes in China. After a strong earthquake, there are a certain period with intensive landslide activity, because the seismic shaking weakens the surface and subsurface, and enhances weathering processe. An increased number of first-failure landslides is indeed recorded after several large earthquakes. However, after peaking upon the earthquake, the rate of post-earthquake landslides will eventually return to pre- earthquake value in less than a decade.

Conclusions: With global climate change, extreme weather events occurred more frequently in the high mountain regions, such as Himalaya regions and Tibetan Plateau. With increasing environmental temperatures and extreme rainfall events, there have been a growing number of geological hazards that produced significant threats and damage to the settlements, hydropower stations, and transportation infrastructures in the Tibetan Plateau. However, the mechanism causing such chains of geological hazards is not well understood. Therefore, studies on glacial-related geohazards induced by climate change in the Tibetan Plateau region have become an emerging hot issue. We introduce five common types of cascading hazards induced by climate change and their possible mechanisms. Some representative cases are discussed. We provide a brief review of studies related to the impact of climate change on chains of geohazards on the Tibetan Plateau and its margins, and highlight future research directions.

MODELING OF THE ACCUMULATION PROCESS OF THE EXCESS PORE WATER PRESSURE FOR PYROCLASTIC SOILS

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Purpose: The generation of undrained excess pore water pressure in saturated granular soils subjected to cyclic loadings, has been studied for many years but it is still an important area of research as demonstrated by the devasting liquefaction-induced damage such as earthquakes (e.g., Italy 2012; New Zealand 2010–2011 and 2016).

Methods: Concerning the undrained response of pyroclastic soils, the mechanism of pore pressure build-up is analysed under undrained conditions to define the susceptibility to liquefaction, whose definition is essentially to define Early Warning Systems for rainfall-induced landslides and for liquefaction phenomena under cyclic and dynamic loading (Olivares et al., 2019, Minutolo et al., 2020).

Results: The results obtained from the experimental program carried out through undrained cyclic triaxial tests (de Cristofaro et al., 2021) performed on different pyroclastic soils, Cervinara (Italy) and Rangiriri (New Zealand), allowed to describe the mechanism of excess pore water pressures within the Steady State Theory using the state parameter ψ of Been & Jefferies (1985). The parameter ψ seems to be useful also in comparing the results obtained on pyroclastic soils with those on ordinary sands. The state parameter ψ has a clear physical significance that could be used to define a more reliable model of undrained pore pressure buildup for soils of different natures.

Conclusions: The research work concludes with the presentation of a new model proposal to define the mechanism of excess pore water pressures as a function of the history and stress state of the material investigated, using parameters (ψ e λ) of the Steady State Theory. In this regard, the parameters of the simplified pore water pressure forecasting model proposed by Chiaradonna et al. in 2016 are explained under the light of the critical state soil mechanics. Functional relationships between the model parameters and those of the critical state has been established using the experimental results obtained on different types of soils. The proposed analytical expressions represent an effective way for the model calibration, overcoming the needs of best-fitting procedures on experimental results of cyclic tests. The modified proposed model seems to be an universal one usable for different materials.

SEISMOGENIC GENESIS OF SECONDARY LIQUEFACTION LANDSLIDES AT OLD LARGE LANDSLIDES IN UZBEKISTAN

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Purpose: We analyzed formation of secondary landslides in ancient cirques caused by various types of seismic impact. It is compared the data of the liquefaction landslides formed in loess and sandy-argillaceous rocks with Pamir-Hindukush earthquakes (date, time, magnitude, depth) at a distance of 370-600 km from the source for the period 1960-2020. At first, lot of data on characteristics and movement types of landslides induced by recent earthquakes were collected. Then, factors densely related to the earthquakes induced landslides extracted based on the collected data.

Methods: For analysis are selected 30 ancient landslide sites (volume from 10.0 to 300.0 million m3) in various tectonic zones in clays, sandstones and limestones covered by loess rocks. Field measurements include study of the frequency, duration of oscillations by data of seismic station and drone surveys.

Results: The resonant frequency vibrations of the soil observed in the central zone of the landslide were 1.5–3.5 Hz, the ratio of vertical to horizontal spectra was from 2.6–3.4 to 5.3–6.2, and the coefficient of soil liquefaction was 35–46. The main feature of ancient landslides is their large scale, they form in the upper part of the slope on the watershed surface - these are linear ledges, overthrust zones, and ring structures. They characterized by micro-hilly relief, head scarps and sometimes presence of small lakes or sinkholes. The watering of the slope confined to various morphometric depressions in combination with tectonic zones and ancient erosional troughs. In the ancient landslide cirques, a single sustained aquifer has not preserved, but there are local areas of a temporary aquifer. The activity of formation of soil movements on the slope timed to the years of maximum precipitation. In the Zerafshan-Alai zone, landslides are common in loess rocks in the area of erosion relief along the northern sides of river valleys in Neogene and Quaternary deposits. In the Baysun zone, landslides developed in the frontal part of the Lyangar thrust in Meso-Cenozoic rocks with Quaternary overlap.

Conclusions: The results of the analysis of modern secondary landslides in ancient landslide cirques showed that out of 30 selected sites, characterized by different shapes of the area of displacement zones, 20 landslides induced by earthquakes at locations over 370-600 km away and no repeated displacements occurred in 10 sites.. There are no secondary repeated displacements in sites, where the entire landslide mass, starting from the watershed, has shifted and eroded, i.e. there is no volume for displacement on the slope and erosion incisions have reached the watershed surface. Large old landslide mass deformations contributed to the generation of mechanically disaggregated material, which may be easily saturated and mobilized during low-frequency, long-lasting seismic action. Regarding the possible earthquake-induced landslides in future, it is need to develop a method to evaluate the failure risk of ancient large landslides existing in the target area and to predict dangerous slopes motions.

EARTHQUAKE-TRIGGERED ROCKSLIDES IN CENTRAL ITALY: A NEW EXAMPLE FROM 2016 SEISMIC EVENT

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Purpose: Earthquake-triggered landslides represent one of the major secondary effects of seismic events, as testified by the numerous rockfalls and rockslides triggered during the 2016-2017 Central Italy seismic sequence. In this work, attention is focused on the largest rockslide triggered by one of the events of this sequence, which is located in the southeastern part of Sibillini Mts. (Umbria-Marche Apennines, Central Italy). Different types of data were collected, and multiple slope stability analyses were performed to reconstruct a reliable triggering model of the landslide.

Methods: Detailed terrain data were collected by coupling traditional field and laboratory activities with advanced remote sensing techniques. In-situ investigations were conducted for measuring joint orientation and roughness, while rock strength parameters were inferred from laboratory tests on rock samples collected within the rockslide deposit. In the second case, we developed a virtual outcrop model (VOM) of the investigated slope through structure-from-motion (SfM) photogrammetry based on UAV (unmanned aerial vehicle) acquisitions. Such a model was used not only for deriving information on the rock mass features at the slope scale, but also for reconstructing a reasonable pre-failure DEM (digital elevation model). Once all the required data were obtained, we performed different slope stability analyses using 3D LEM (limit equilibrium method) with PLAXIS LE software. In particular, we considered both static and earthquake loading conditions, the latter through Newmark permanent displacement analyses.

Results: The performed activities allowed us to reconstruct a slope model suitable for performing a back-analysis of the occurred rockslide. In this sense, from the simulations carried out under static conditions we inferred a realistic scheme of the landslide body, revealing the role of specific discontinuity sets in failure enhancement. These sets have also been linked to the general, morphostructural context of the area. The analyses conducted assuming the earthquake loading are consistent with the real scenario and allowed us to preliminary assess several aspects concerning the triggering conditions.

Conclusions: In this work we reconstructed, via back-analysis, a rockslide occurred in central Apennines during the 2016 seismic sequence. The performed analyses, carried out under static and earthquake loading conditions, allowed us to define a realistic triggering scenario, pointing out the main features of the landslide event related to the slope conditions preceding failure. The obtained results can provide useful insights about the response of fractured rock slopes to moderately high-magnitude earthquakes typically occurring in the Apennines.

ON THE INITIATION AND MOVEMENT MECHANISMS OF A MASSIVE COSEISMIC LANDSLIDE TRIGGERED ON AN EXTREMELY GENTLY SLOPE: A CASE STUDY IN JAPAN

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Purpose: The 2008 Iwate-Miyagi inland earthquake triggered a lot of landslides, resulting in great damage to local properties and the loss of many lives. Among these landslides, the Aratozawa landslide was the largest, which involved the movement of an old landslide about 100 m thick with a volume of about 67 million m3. The displaced landslide material traveled a long distance along a very gently sliding surface. This study aims at unraveling the initiation and movement mechanisms of this massive coseismic landslide.

Methods: We surveyed the S-wave profile of the displaced landslide material by a surface-wave technique called multichannel analysis of surface waves (MASW) and microtremor array measurement. We examined the boring cores that were obtained after the landslide event to identify the sliding surface. We took samples from the soil layers along the sliding surface and conducted ring shear tests on the samples to examine the drained/undrained shear behaviors. We synthesized the possible seismic loadings on the sliding surface by using the seismic records of the earthquake that were obtained on a nearby dam site and applied the loadings to the samples in ring shear tests. measured the shear-wave-velocity of the landslide deposits by a surface-wave technique.

Results: The boring survey on the displaced landslide body revealed that the sliding surface was developed along the alternate layer of fine-grained sandstone and siltstone. The sliding surface is sloped approximately 1 to 2 degrees. Undrained shear tests on the samples showed that the soil layers along the sliding surface are highly liquefiable. Undrained shear tests by the coseismic loadings showed that initiation of the landsliding could be triggered with the exitance of high groundwater table before the earthquake.

Conclusions: The massive Aratosawa landslide traveled more than 300 m along a sliding surface sloped approximately 1~2 degrees. The S-wave profiles of the landslide mass and soil layer outside of the landslide area reveal that the soil layers near the sliding surface are disturbed, while the soil layer structure within the massif is basically undisturbed, indicating most of the landslide blocks presented the feature of en mass sliding. Undrained ring shear testers on sand from the formation that formed the landslide slip surface (alternating sandstone and siltstone) revealed that very small shear strength could be reached at the steady state, resulting in very small apparent friction angles for the landslide. Cyclic shear tests on the same sample indicated that this massive landslide with an extremely gentle sliding surface could not be triggered without the exitance of a high level of groundwater or the displaced landslide materials were not in large scale.

THE DIFFICULT PREDICTION OF EARTHQUAKE-INDUCED LANDSLIDE DISPLACEMENTS: THE CASE OF GAGGIO MONTANO (NORTHERN APENNINES, ITALY)

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Purpose: One of the most damaging side effects associated with seismic shaking within a certain distance from the seismogenic source is possible landslide movements. These phenomena could have devastating consequences on local communities even with low-intensity shaking. To mitigate these risks, it is crucial to have detailed knowledge of how landslides behave under seismic shaking, with particular attention to the behavior of the ground under rapid seismic pressure. The study case concerns a complex slow-moving landslide that primarily affects clay soils in Gaggio Montano (northern Apennines, Italy) a zone with medium seismic risk. The purpose of this study is to evaluate the seismic response of the slope and estimate the seismic-induced landslide movements using the Newmark method.

Methods: Firstly, we compiled a database of the existent geognostic investigations (cores, inclinometers, piezometers, and CPT) and of the new geophysical surveys (HVSR and MASW) specifically acquired for this study. This allowed us to realize a detailed geological model of the slope and the landslide body. Secondly, we ran a 2D-numerical model of the seismic response of the slope. This allowed us to evaluate the topographic and stratigraphic effects in response to hypothetical earthquakes with a return period of 475 years. Finally, we applied the Newmark method to estimate seismic-induced landslide movements. A detailed sensitivity analysis was performed to account for the strong uncertainty in the data, especially regarding the geotechnical input parameters. In addition, we evaluated the theoretical results with an experimental innovative method, which can also be implemented in other cases, based on Sentinel-1 satellite data. The main idea is to investigate if exist any correlations between displacements and the occurrence of earthquakes (maximum horizontal acceleration – PGAh) in the vicinity of the site during the analyzed period (2016-2021).

Results: The results show that the geotechnical parameters dramatically influence seismic-induced displacements. This highlights the limitations of the conventional approach and the difficulty in predicting the response of existing landslides to seismic shaking. Finally, the experimental monitoring made it possible to calibrate the expected displacements below a certain threshold, depending on the PGAh (measured or estimated) in situ.

Conclusions: Seismic-induced landslides pose a severe threat to communities in seismically active areas. This study's findings highlight the need for a detailed understanding of landslide behavior under seismic shaking to mitigate these risks. The sensitivity analysis shows that the geotechnical input parameters can significantly affect the results of seismic response modeling. Therefore, future studies must improve the accuracy of geotechnical input parameters to improve the predictability of landslide movements. Concerning the planning decision, we suggest systematically using the innovative method proposed here to evaluate the result of seismic induced displacement.

WHAT TRIGGERED EL GUASIMO LANDSLIDE? DISTINCT ELEMENT ANALYSIS OF A LARGE PALEO LANDSLIDE IN THE COLOMBIAN ANDES

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Purpose: Large landslides are a rather rare phenomenon that is often related to extreme weather events or earthquakes. They do however have a high destructive potential and the occurrence of such large landslides in urbanized areas would be disastrous. Understanding the circumstances and mechanisms that have led to the formation of such large landslides, which are often still easily recognizable in today's landscapes, is key to assessing the potential for future disasters. This is especially true in the face of an escalating climate with an increasing frequency of extreme climatic events and the trend of rapid urbanization in landslide prone and seismically active regions. El Guasimo landslide in the Cauca Valley of the Colombian Andes is an example of such a large landslide. It has been extensively studied and different theories exist on its formation, involving either heavy rainfall or an earthquake, both plausible scenarios considering the tropical climate and the location along the active Cauca-Romeral fault system. In this study, we used a distinct element numerical modelling approach to back-analyze El Guasimo landslide and try to better understand the triggering mechanism.

Methods: In a first step, the pre-slide topography has been reconstructed for a two-dimensional profile using a 10 m digital elevation model. Then, we implemented the created profile into the two-dimensional distinct element code UDEC (Itasca, version 7.0) to analyze the stability of the slope exposed to static and dynamic impacts, such as gravity load, varying friction angles and cohesion values, the existence of a sliding surface, different water tables, and seismic load.

Results: In the static analysis, critical values for the friction angle and cohesion were investigated using the strength reduction method to estimate the factor of safety. The friction angle seemed to have the highest impact, and the slope only failed for values of 15° or lower. Furthermore, the simulation results indicate the presence of a weak zone or sliding surface. Different static water tables (50 m, 20 m, and 0 m below ground surface) did not seem to have a major impact on the overall slope stability, although simulations considering water in the slope in general yielded higher displacements. The displacement analysis and failure reproduction under dynamic seismic load shows that the highest displacements and velocities could be simulated under intense seismic load and with water in the slope.

Conclusions: To conclude, our answer to the question "What triggered El Guasimo landslide?" is that based on our simulations, a scenario with a combination of a strong earthquake and elevated water levels acting on a slope with a suspected weak zone is most likely.

EARTHQUAKE-TRIGGERED FAILURES AND SEISMIC RESPONSE OF SUBAQUEOUS SLOPES IN SWISS LAKES

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Purpose: Subaqueous mass movements in lacustrine environments can generate tsunamis. Most frequently, these mass movements are triggered by earthquakes, as happened, for example, in 1584 in Lake Geneva or 1601 in Lake Lucerne in Switzerland. To understand the potential for the repetition of such events, the seismic response of subaqueous lake slopes and critical earthquake ground motion should be evaluated. For this goal, we (i) analyzed the records of seismically-triggered subaqueous slope failures (some of which generated tsunamis) in Swiss lakes and (ii) deployed Ocean Bottom Seismometers (OBS) in Lake Lucerne to record ambient vibrations and earthquakes.

Methods: For the site response analysis, we used the OBS recordings from Lake Lucerne. First, we estimated the Horizontal-to-Vertical (H/V) spectral ratios using ambient vibrations (H/Vnoise) and earthquake recordings (H/Vearthquake). Next, we used the Empirical Spectral Modelling and Standard Spectral Ratio techniques to estimate site amplification functions (AF). For the back analyses of past events, we collected a dataset of (i) historical and instrumental earthquakes that have or have not triggered subaqueous slope failures (sometimes, tsunamigenic) in Swiss lakes and (ii) the locations at subaqueous slopes in Swiss lakes that have or have not failed as a consequence of those earthquakes. This dataset was used to apply the Swiss Ground Motion Models and derive the threshold for triggering subaqueous slope failures in terms of ground motion, macroseismic intensity, and magnitude-epicentral distance relationship.

Results: The H/V ratios show that the fundamental frequency of resonance for the investigated sites varies between 0.5 and 3.5 Hz. The ground-motion AF were estimated using the recordings of local and near-regional earthquakes. The estimated amplification levels are very high and often exceed the values of 50-100 in the investigated frequency range. No clear signature of nonlinear site response was yet observed in the H/Vearthquake or AF. Finally, the seismic response of investigated sites is spatially variable on both local and regional scales (Figure 1). Through the back analyses of past subaqueous-slope failure-triggering events, we estimated critical ground motion (PGA, PGV, and PSA at selected spectral periods) at Swiss reference rock conditions. Also, we derived the critical macroseismic intensity at reference rock conditions and critical threshold in terms of earthquake moment magnitude and epicentral distance relationship.

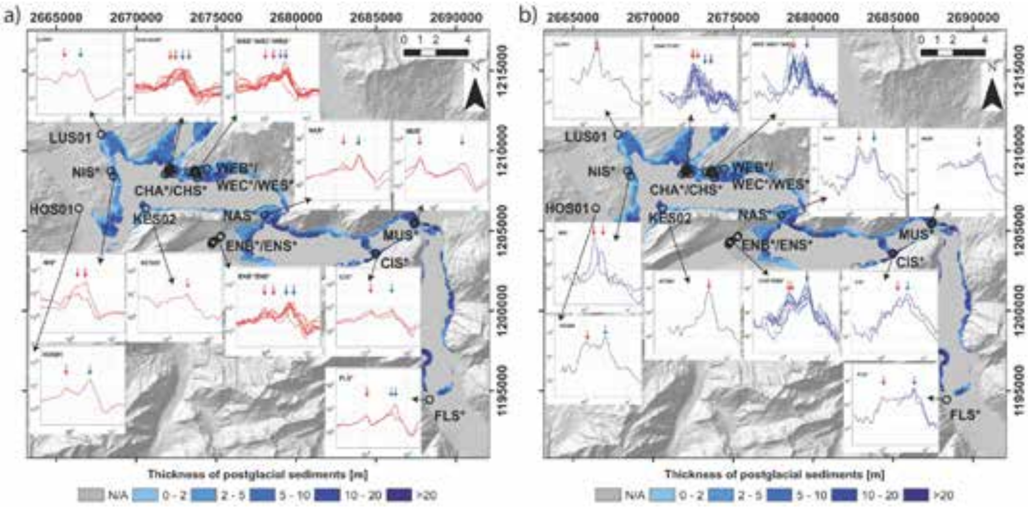

Fig. 1: a) H/Vnoise and b) AF estimated at subaqueous slopes in Lake Lucerne on top of the map of the thickness of postglacial sediments. Red and blue curves correspond to the H/Vnoise and AF at each site, respectively. The down-pointing red and blue arrows show the fundamental frequency of resonance and the frequency of the second peak, respectively.

Conclusions: Performed investigations reveal the prominent and variable response of lake slopes to seismic triggers and point to their high susceptibility to failure in case of strong earthquakes. Using the past events, we defined critical thresholds (at reference rock conditions) required to trigger subaqueous slope failures. To merge the information derived for reference rock conditions and the actual seismic response of lake slopes, experimental laboratory data and/or in-situ recordings of strong earthquakes are required.

SESSION 6.9

LANDSLIDE STUDIES IN ITALY: STATE OF THE ART AND FUTURE PERSPECTIVES (part II)

DATA-DRIVEN MODELING TECHNIQUES FOR LANDSLIDE PREDICTION: PRESENT AND FUTURE CHALLENGES

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Purpose: The literature on data-driven models for landslides' prediction has historically seen most of its efforts dedicated to the use of binary classifiers. These are used to distinguish locations prone to slope failures from stable ones. As for the structure, most of these tools have been inspired to spatial statistics, with the aim of capturing the natural susceptibility of a given landscape to landslides. Beyond this topic, early-warning systems have been employed to capture the influence of meteorological triggers, by estimating rainfall-thresholds over fixed temporal windows. Conversely, the earthquake-induced landslide counterpart has seen the community's effort invested towards near-real-time predictive models. In any of these two, despite the substantial improvement with respect to the pure spatial case typical of the traditional susceptibility assessment, two elements of the landslide hazard definition are still mostly neglected. The first one corresponds to the landslide intensity, or measure of the threat a given landslide may exert on potentially impacted infrastructures. The second one pertains to the temporal characteristics of the likelihood, all too often estimated with relatively simple tools rather than modern space-time data-driven models. This presentation aims at summarizing what the next generation of data-driven solutions may offer when called upon to fulfil the standard definition of landslide hazard: i.e, predicting where landslides may occur, when or how frequently they can take place and their associated intensity measured in landslide area (or area density).

Methods: We will see the use of space-time statistics as well as deep learning solutions to estimate landslide hazard. In doing so, we will go through models capable of fitting one statistical distribution at the time, as well as more than one, touching on joint probability or ensemble modelling.

Results: The presentation will cover all aspects of the landslide hazard distribution. The spatial occurrence probability typical of susceptibility models being extended to the space-time context. As for the landslide intensity, we will explore the use of tools capable of predicting how large landslides may be per slope, or their proportion with respect to the slope extent. Ultimately, part of the presentation will be dedicated to the use of such tools as simulators, thus estimating landslide hazard not only in current conditions but also for targeted climate scenarios.

Conclusions: The presentation is meant to stimulate an open discussion on where the landslide community can be headed in the future, when it comes to data-driven solutions.

MODELLING RAINFALL-INDUCED LANDSLIDES AT A REGIONAL SCALE, A MACHINE LEARNING BASED APPROACH

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Purpose: In Italy, rainfall represents the most common triggering factor for landslides, thus many Italian civil protection agencies have been working on defining effective warning systems, at a regional scale, relying on the definition of empirical correlation between rainfall and landslide, obtained from historical data of landslide occurrence. Such models are mostly obtained by deriving a mathematical equation which represents the threshold beyond which landslides have occurred in the past, and it is assumed they will occur in the future. The present work aims to model rainfall-induced landslides at a regional scale in the Liguria region (Italy), through the application of a Machine Learning based approach.

Methods: The model applies a polynomial kernel regression algorithm to estimate, at daily time steps, the number of landslides corresponding to a combination of five observed predicting variables: The Alert Zone, soil moisture, antecedent accumulated rainfall over 12 hours averaged over the Alert Zone area, the peak over 3 hours over an area of 100 km2, the time of the year. The use of multivariate analysis allows to increase the complexity of the empirical relationship by exploiting other factors apart from the rainfall. Moreover, the model not only defines the possible occurrence of landslides, but also estimates the number of events per Alert Zone, thus providing information about the expected scenario, in accordance with the Regional Civil Protection guidelines (D.G.R. n. 1116 del 23/12/2020), that identifies four different alert levels based on the number and spatial distribution of occurring landslide phenomena (Table1).

Scenario	**# landslides**	**Extent**
Low	0-2	low probability of phenomena
Ordinary	3-5	localized phenomena
Moderate	6-13	widespread phenomena
High	> 14	phenomena extended over an AZ

A dataset from 2014 to 2019 was used for calibration and validation, corresponding to a catalogue of 359 days with conditions that have resulted in 2191 shallow landslides.

Results: Test of the calibrated model was carried on considering the year 2018. The model shows good performance, with a Root Mean Squared Error RMSE = 2 and mean absolute error MAE = 1. However, results show a strong dispersion, especially for low values. The predicted number of landslides was converted to a scenario, according to Table 1 and compared with the scenario obtained from the registered landslides on the same day. Results were analyzed by means of contingency tables and skill scores. Statistically, the model is found to have 93% efficiency with a likelihood ratio of 13.4. A feature importance analysis revealed that soil moisture represents the most relevant predictive variable for the model.

Conclusions: The model described provide good results in the prediction of the number of occurred landslides based on selected observed hydrological inputs. It constitutes a prototypal version of a predictive model that will be implemented in the future, where observed predictive variables will be replaced with values obtained by forecast models operational at ARPAL.

STATE OF THE ART OF SATELLITE SAR INTERFEROMETRY PRODUCTS FOR LANDSLIDE HAZARD MITIGATION AT REGIONAL SCALE

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Satellite Synthetic Aperture Radar Interferometric (InSAR) data have been long exploited for detecting and mapping slow-moving ground surface displacements due to their millimeter accuracy, non-invasiveness, unique possibility of historical back analysis and wide area coverage. In this work a scientific state of the art on satellite InSAR products for landslide hazard mitigation at large scale in Italy is provided.

In the last decades, satellite InSAR techniques have widely used for landslide mapping and monitoring, for back analysis, characterization, static mapping of landslides, and for updating landslide inventories and landslide state of activity.

Nowadays, the highly improved computing capacity, the enhancement of processing techniques and the availability of C-band Sentinel-1 SAR data (from the European Space Agency) have opened new opportunities for InSAR applications for landslide hazard analyses. At this regard, a useful screening of the European territory is currently offered by EGMS (European Ground Motion Service) that represents a baseline for ground deformation analysis at continental, national and regional level.

Within the framework of space borne InSAR management for landslide studies, Italy is a country at the forefront on the international background. The first national scale PSI (Persistent Scatterers Interferometry) mapping (i.e., Not-Ordinary Plan of Remote Sensing) dates back to 2009, relying on historical SAR archives of ERS and ENVISAT satellites. In 2014 this project has been updated for some areas of the Italian territory with PSInSAR data derived from COSMO-SkyMed images acquired as part of the MapItaly Project. Moreover, some Italian regions (Tuscany, Veneto, Valle d'Aosta, Friuli Venezia Giulia, Lazio) and research institutions are exploiting services of monitoring of the deformative scenario based on the systematic processing of Sentinel-1 data and providing velocity maps and time series of displacement achieved by PSI technique. These projects allow to point out the highest ground motion rates and most hazardous sites for civil protection and land management purposes.

Significant improvements have been done during the last years, in data processing methods and capacity, however the expert interpretation and applications of large volumes of interferometric results represent an issue to the prompt exploitation of the retrieved information. In this regard, different post-processing approaches, machine learning modelling and semi-automatic and automatic landslide mapping methods at large scale have been recently proposed.

X- and C-band InSAR data have been recently exploited for characterizing landslides in the area affected by the 2016–2017 seismic sequence of Central Italy and for supporting decisions about post-seismic reconstruction criteria. At international level these data are also systematically used for the rapid detection of slope instabilities in open pit mines.

Future perspectives on a more extensive exploitation of multi-temporal and multi-frequency InSAR data by private and administrative institutions will be fostered by the new IRIDE satellite constellation and services segmentation for Earth Observation expected by 2026. Lastly, new possibilities could come from the systematic exploitation of L-bands SAR mission that would enhance the capabilities of better investigating non-urbanized and vegetated areas, as well as the possibility of geosynchronous missions with high revisiting time.

APPLICATION OF SENTINEL-1 PARALLEL-SBAS DATA TO UPDATE THE STATE OF ACTIVITY OF NATIONWIDE LANDSLIDE INVENTORY MAPS: THE EXPERIENCE OF ITALY

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Purpose: Landslides are a major threat worldwide, causing a considerable number of casualties and damage to structure and infrastructures. Landslides have a huge impact on the Italian territory, being one of the countries historically most affected. The first and foremost important question to address landslide risk is to have a complete awareness of the landslide scenario in an area, with detailed information on the state of activity of landslides. In this sense, satellite technologies, especially Synthetic Aperture Radar (SAR), through the implementation of MTInSAR (Multi Temporal Interferometry SAR) methods, represents an ideal solution for the detection and update of landslides in large areas, such as whole nations. In this work, Sentinel-1 data, acquired between 2014 and 2018 over the whole national territory of Italy and processed by means of P-SBAS (Parallel Small Baseline Subset) algorithm, were used to update the national IFFI landslide inventory (Inventario Fenomeni Franosi in Italia,in Italian, Landslide Inventory in Italy, Trigila et al.2010).

Methods: To update the IFFI inventory, a matrix approach was adopted: the initial landslide State of Activity (SoA) was defined considering the displacement velocity projected along the slope (Vslope) computed with Envisat data (time interval 2003-2010), thus compared with the SoA derived from Vslope with Sentinel-1 (S1) (time interval 2014-2018). To discriminate between stable and unstable landslides, a mean deformation velocity threshold, corresponding to 2 times the standard deviation (σ) of the final Measurements Points (MPs), has been chosen. The estimated standard deviation is equal to 3.5 mm/year, thus implying that the landslides with velocities higher than 7 mm/yr were considered active. Additionally, a reliability matrix was defined by using the MPs density and the standard deviation of the Sentinel-1 deformation velocity of each detected landslide. Finally, the displacement components (horizontal (East-West) and vertical), retrieved by combining ascending and descending LOS (Line of Sight) measurements obtained with MTInSAR, were estimated, thus making more effective the comparison with the considered types of landslides.

Results: The final computation of the SoA values has regarded 46,217 and 56,133 landslides for the Envisat and the S1 datasets, respectively. These numbers have been retrieved considering areas that have at least 1 MP. According to the performed analysis, about 37,000 were classified as dormant and 8000 as active, for the Envisat data, while for S1, about 41,000 landslides show a dormant SoA, and 14,000 an active one. As regards the reliability analysis of the landslides identified through the S1 MTInSAR measurements, a high and very high reliability was assessed for about 19,000 landslides (36% of the landslides whose SoA was defined). The analysis of the vertical and horizontal displacement velocity components showed that the Deep-Seated Gravitational Slope Deformations (DSGSDs) and the slow flows are characterized by a significant horizontal component, while slides and complex landslides have an important vertical one.

Conclusions: Having constantly updated landslide inventory maps is a crucial task for an effective territorial planning activity, especially in a country like Italy. Fully automatic processing chains like P-SBAS workflow can be very useful for a fast and systematic update of landslide inventories, providing significant support to risk reduction practices.

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SATELLITE RADAR ANALYSIS FOR LANDSLIDE EVENTS

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Purpose: Landslides pose a significant geological hazard in Italy, causing considerable damage to the environment and infrastructure. With over 100,000 landslides mapped across the country, their identification and monitoring are crucial for investigating their behavior, assessing potential impacts, and preventing further occurrences. From the nineties, Synthetic Aperture Radar (SAR) imagery, acquired by satellite sensors operating at different frequencies, has proven to be a valuable tool in landslide research, offering insights into urban and vegetated areas. The analysis of SAR imagery can vary depending on the purpose, such as identification, characterization, back-analysis, or monitoring of landslides.

Methods: In recent decades, several ground deformation investigation techniques have been developed, each with its own strengths and limitations that must be considered for the appropriate case study. For slow landslide investigation, the most commonly used technique is Multi Temporal Interferometric SAR (MT-InSAR), which generates deformation maps and time series for each point, enabling the examination of point behavior over the entire image period. Processing algorithms have been refined and improved since the 2000s, leading to increasingly accurate and informative ground deformation maps. More recently, the Sentinel-1 constellation of the European Space Agency (ESA) has facilitated continuous InSAR monitoring with short revisit times over very wide areas (>1M km2), allowing the development of data mining algorithms for identifying points with abrupt trend variations, supporting the identification of critical situations. Furthermore, an automated and unsupervised approach has been designed to detect recurrent time series patterns, based on data dimensionality reduction and clustering, via the Principal Component Analysis (PCA) and K-means techniques, enabling the investigation of differential movements within landslides.

For fast-moving landslides, other approaches can be used, namely: (i) Speckle tracking, detecting and measuring displacement values by working on the amplitude information contained in pre- and post-event SAR images, (ii) offset tracking (or Rapid Motion Tracking - RMT), similar to speckle tracking, but applied to stack of images and allowing one to retrieve displacement time-series, (iii) conventional differential InSAR (DInSAR), generating simple interferograms between a pre- and post- event image.

Conclusions: The use of SAR images for characterizing and monitoring landslides significantly improved over the past decades. The systematic capture of SAR images across the globe has spurred the development of sophisticated SAR data processing algorithms, based on both amplitude and phase information. The availability of free InSAR databases has been increasing steadily, with regional and national governments, as well as the European Union, investing significant resources in remote sensing tools for landslide monitoring. One notable example of such databases is the European Ground Motion Service (EGMS) provided by the Copernicus Land Monitoring Service (CLMS) offering both horizontal (east-west) and vertical displacement measurements across Europe.

In summary, the increasing availability of SAR images, coupled with the development of sophisticated SAR data processing algorithms and free InSAR databases, has significantly enhanced our ability to monitor and predict landslides. The integration of these tools with conventional observation methods and geological maps provides a comprehensive understanding of landslide processes, thus enabling effective hazard mitigation measures.

CASCADE-FORWARD PROPAGATION OF A COMPLEX EART SLIDE /EARTH FLOW DETERMINED BY USING SENTINEL-2 DIGITAL IMAGE CORRELATION: THE VALORIA CASE STUDY (NORTHERN APENNINES, ITALY)

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Purpose: The Valoria landslide is a complex earth slide/earth flow characterised by a total horizontal length of 3.5km and has a vertical development of about 900m. Because of repeated reactivations during the 2001-2009 period that continually interrupted traffic along the crossing main road, local authorities built in 2009 an overpass bridge in the track zone to preserve the viability in case of further reactivations. Unfortunately, a recent event started with a paroxysmal reactivation in September 2020 and slowly ceased in March 2021.

Methods: In order to determine the spatial and temporal activity of the Valoria landslide a total of 14 acquisitions by Sentinel-2 satellite covering the period from September 2020 to March 2021 have been analysed using the IRIS© Digital Image Correlation (DIC) software developed by NHAZCA s.r.l. (spin-off from “La Sapienza” University of Rome).

Results: By using the DIC methodology it has been possible to constrain the first phase of the landslide reactivation in September 2020 with a retrogressive style and as a translational movement. While, on a first instance, alert by local population was given in October. Additionally, the cascade-forward propagation has been depicted. More in detail, it is characterized by several impulses of up to 40m of planimetric displacements that are chronologically delayed in the downslope direction.

Conclusions: As a matter of fact, it has been proven that satellite based DIC approach represents a valid methodology for temporal and spatial constraining the activity of large active landslides.

SHALLOW LANDSLIDES REGIONAL MODELLING CONSIDERING THE MECHANICAL EFFECTS OF VEGETATION: TWO ITALIAN CASE STUDIES

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Purpose: The presence of vegetation on hillslopes reduces the slopes susceptibility to the shallow landslides, and one of the major stabilizing actions exerted consists in a mechanical reinforcement of the soil through the root systems. Root reinforcement spatial variations are therefore a significative factor to be considered in distributed slope stability analyses, however, natural variability of the parameter makes challenging its integration into the models. The study arose from the purpose of overcoming two mains lacks in the field of regional distributed slopes stability analyses: a distributed slope stability model capable of quick processing in which the root reinforcement is considered; an efficient approach to estimate the root cohesion tested in very wide areas and simulating extended periods. The ultimate goal is providing increasingly efficient and accurate shallow landslides forecasting tools for civil protection purposes.

Methods: Regional slope stability simulations for two case studies in Italy considering the effect of the root reinforcement were carried out using a physically-based distributed slope stability model, the HIRESSS (HIgh REsolution Slope Stability Simulator), capable of rapid processing even in case of wide areas thanks to its parallel structure. The simulator had been modified to consider the root reinforcement phenomenon while computing the factor of safety in probabilistic terms adopting a root cohesion model commonly used in literature. An approach to estimate regional variations of root cohesion had been conceived based on plant species distribution, root cohesion literature values and Monte Carlo simulations. Simulations results had been processed, analyzed, and compared to evaluate the adopted approach to estimate the root cohesion at the regional scale and the impact of the root cohesion on the failure probabilities.

Results: The comparative analyses of the simulations performed inserting or not the root reinforcement highlighted that the impact of this parameter has been more evident in the outputs of the not rainy days, in terms of failure probabilities. The additional cohesion provided by the root systems produced higher values of factor of safety to some extent but concerning the failure probabilities obtained through the Monte Carlo iterations, the root cohesion had a minimal impact on the results, and this behavior was particularly clear when the saturated conditions were reached. The finding is attributable to the model adopted to integrate the root cohesion effect.

Conclusions: The research allowed to test a commonly adopted model of the root cohesion by means of applications of a distributed slope stability simulator in regional areas, finding that a different root cohesion model could be preferable in the context of the shallow landslides, in similar areas of the study, and working in terms of failure probabilities. This different model should represent the component of the cohesion due to the presence of the roots in the soil as following a relation of decreasing with the increase of the soil water content different from the relation adopted for the “standard” soil cohesion. In this perspective, new studies on the relation between root cohesion and soil moisture will be extremely useful.

SOCIAL MEDIA AND TRADITIONAL SENSOR INFORMATION FOR DETECTING NATURAL HAZARD IN ITALY

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Purpose: Mass media are a new and important source of information for any natural disaster, mass emergency, political event, or extreme weather event affecting one or more communities in a country, providing a relatively high temporal and spatial resolution. Several techniques have been developed to mine news different natural hazards, such as floods, but rarely applied to landslide news. Traditional methods such as the use of ancillary data, remote sensing or technical reports are the most used to redact landslide inventories, but few useful in areas without traditional sensors. In this sense, collecting articles from social media would afford to detect natural hazards directly. Further, the combination of social media data and traditional sensors could improve warning systems to enhance the awareness of disaster managers and citizens about emergency events.

Methods: The algorithm Semantic Engine to Classification and Geotagging News, based on a semantic engine, automatically retrieves information about landslide events at the national scale from Google News. From 2010 to 2019, more than 30 thousands landslide news have been harvested over Italy. The dataset has been classified manually into classes based on their issue, temporal and spatial relevance. This classification makes possible to outline the temporal and spatial distribution of events, their media impact and the design of hazard maps on regional and provincial scale. Furthermore, different data sources were analysed, filtered and homogenized to obtain correlations and information about landslide events and direct consequences in Italy for 10 years.

Results: The dataset classified allowed to identify the news describes the ongoing event or their consequences and to reject the data not appropriate, reducing the data to be processed and creating a landslide inventory from social media. The retrieved news data have been compared with traditional sensors (e.g. rain gauges) and official reports about victims, funds for soil protection and hazard maps. Landslide news showed an increasing trend from 2015–2019 period, in contrast with rainfall data and reported expenses, while the victims number remained constant. The spatial distribution revealed that there were more landslide news and fatalities in the northern regions. A similar trend was found in the frequency of relevant rainfall events. Conversely, the distribution of earmarked funds was more concentrated in southern Italy than in northern Italy.

Conclusions: This work allowed to show as the use of automatically retrieved data from online newspapers allows generating a reliable landslide inventory. Such data can be utilized as a proxy for hazard assessment over wide areas and to examine the distribution of the phenomena and their correlation with other variables providing a fast tool for rapid hazard assessment for support public authorities and decision-makers.

THE ITALIAN DATABASE OF EARTHQUAKE-INDUCED GROUND FAILURES (CEDIT): NEW RELEASE AND DEVELOPING APPLICATIONS

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Purpose: The Italian Catalogue of Earthquake-Induced Ground Failures (CEDIT – Catalogo degli Effetti Indotti da Forti Terremoti in Italia) collects evidence of ground effects induced by historical earthquakes occurred in Italy. Since the 1997 the catalogue has been managed by the Research Centre for Geological Risks of Sapienza University of Rome (CERI). Its latest release, online by 2021, contains 4041 earthquake-induced ground effects by 175 seismic events from 1117 A.D. to 2022.

Methods: The last release of the catalogue allows a free online consultation based on WebGIS and Web Map Service (WMS) optimised for portable devices. The induced ground failures have been catalogued following a systematic review of the documents in the historical archives and searching in the published literature; ground failures induced by recent earthquakes were directly field surveyed. An application for smartphones and tablets was customised for performing the automatic inventorying of the effects; it can be directly interfaced with the online database. The info useful for effect description is linked to each induced ground effect, including geolocation, typology, macroseismic intensity of the point in which it occurred, lithotype involved, volume, interference with anthropic works and other metadata. As far as the historical effects are concerned, however, four geolocation classes were considered, with increasing error, depending on the uncertainty in exact geolocation (i.e. error ranges from 1 up to 30 km depending by the class).

Results: The last release of the CERI database includes 4041 earthquake-induced ground effects inventoried in more than 1000 administrative localities of Italy and are related to 175 historical earthquakes. In particular, 2242 ground effects are represented by landslides (55% of the total collected effects), 981 ground effects are represented by ground cracks (24 % of the total), 486 ground effects belong to the liquefactions category (12% of the total), 194 ground effects are composed by ground changes (5% of the total) and, finally, 138 are associated to surface faulting ground effects (4% of the catalogue). The most recent earthquake which has been included in the CEDIT catalogue is the 2022, 5.5 Mw, Marche coast earthquake, which induced 18 effects surveyed between the Conero promontory and that of San Bartolo, south of Ancona and north of Pesaro respectively.

Conclusions: The CEDIT catalogue results a useful tool for analysis of scenarios based on occurred earthquake-induced effects in the National territory. Furthermore, starting from the distribution of the inventoried effects, it has been possible to implement susceptibility studies through artificial intelligence applications which up to now provided expected distributions of earthquake-induced landslides.

SESSION 4.5

ROCKFALL DATA: COLLECTION METHODS, ANALYSIS AND USE FOR HAZARD AND RISK ASSESSMENTS (part I)

DATA COLLECTION AND 3D MODELING APPROACHES TO SUPPORT ROCKFALL RISK MANAGEMENT ALONG ROADWAYS IN COMPLEX GEOLOGICAL SETTINGS: YOSEMITE NATIONAL PARK (USA)

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Purpose: Roadways in geologically complex mountainous areas are often characterized by heterogeneous patterns of rockfall risk, the correct evaluation of which requires the support of high-resolution simulations. At the same time, practical risk analysis requires sound and cost-effective data collection and model calibration practices. We tested a high-resolution, wide-area rockfall modeling approach targeted to rockfall risk evaluation along roads in Yosemite National Park, a major natural asset that attracts millions of visitors each year. The geological setting of the area, with tens of kilometers of 1000 m high granite cliffs, makes it particularly susceptible to rockfalls, while its geomorphological complexity makes runout predictions uncertain. During the ten years from 2010 to 2020, 640 rockfall events were recorded; almost half of these caused damage to the road network. Approximately 300 rockfalls affected the Merced River corridor (the preferred entrance way of 30% of the visitors), causing road damage, temporary closures and fatalities. Because National Park policies generally preclude mitigations on natural slopes, risks along roads are mitigated through traffic management practices based on local hazard evaluation that remains challenging in these complex geological conditions. Thus, we performed high-resolution 3D rockfall simulations using the Hy-Stone runout model over an area of 18 km^2, which contributes to rockfall hazards along two road sections within the park, including El Portal Road.

Methods: We based our models on existing datasets (1m LiDAR DEM, canopy height, geological and vegetation maps), the unique database of Yosemite rockfalls (1857-2020), and targeted field surveys of infrastructure, rockfall paths and deposits, and damage caused by previous rockfalls. We identified rockfall sources using a morphometric approach refined by detailed mapping of rockfall evidence and unstable areas, and classified sources into “cliff” and “roadcut” (engineered). We focused on field evidence collected in the aftermath of the 2017 Parkline rockfall to reconstruct the location and size of 4700 blocks and obtain a reference block size distribution for the simulations. We mapped Quaternary deposits at the scale of consideration and reclassified deposit and vegetation types in categories relevant to rockfall interactions. Hy-Stone simulation parameters were calibrated by the back analysis of a set of occurred rockfalls, for which field-based evidence was collected by NPS and USGS, by optimizing the fit between simulated and observed arrest locations and volumes.

Results: We performed forward simulations for the study area considering “cliff” rockfall sources and two different block volume scenarios with stochastically variable (realistic) or constant volumes (100 m3, worst-case). We validated the results (block frequency, velocity, energy, and height) against the historical and field databases making it possible to perform a quantitative evaluation of rockfall susceptibility and hazard along the reads using empirical and probability-based approaches.

Conclusions: Our models, combining robust 3D simulations with detailed field data, allow the characterization of rockfall susceptibility and hazards over a large complex area and along road sections with the spatial accuracy typical of design-oriented, site-specific studies. The models also provide robust inputs to quantitative risk analysis that will allow optimizing risk management and granting safer access to the park.

CORRELATION OF ROCKFALL FREQUENCY WITH OVERHANG DIMENSIONS AT FLYSCH ROCKY WALLS

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Purpose: Assessing the expected rockfall frequency remains challenging for the quantitative rockfall hazard assessment, in particular where inventories are missing. The objective of this work was to investigate the correlation between the frequency and the area of rock overhangs at rocky slopes.

Methods: To study the rockfall frequency along the N-634 coastal road in the Basque Country, connecting Zarautz and Zumaia, a rockfall inventory covering over 4 decades was compiled. It includes descriptive information for the rock size and the road blockage, which was interpreted to classify events into 5 volume classes, from A to F (≤0.5, 0.5-5, 5-50, 50-500, 500-5000, >5000 m3). Seven sections, from 125 m to 560 m length, of weathered flysch rock mass forming overhangs were studied. Events for each section range between 13 and 91. 3D models of the slopes were developed using a Terrestrial Laser Scanner (TLS) and terrestrial plus aerial photogrammetry from UAV (Figure 1). The overhangs were identified using the Discontinuity Set Extractor (Riquelme et al. 2014). Their surface was calculated with a procedure which consists in the filtering of the overhang points from the point cloud, the plotting of envelop polygons and the calculation of their area.

Fig. 1: (Left) View of the overhangs; (Right) Point cloud obtained by terrestrial/aerial photogrammetry.

Results: The correlation between the rockfall frequency and the sum of the overhang areas was calculated. A good (x2=0.85) linear correlation was found between the number of all events and the total area, and a very good linear correlation (x2=0.95) for the respective normalized values per linear road meter. The correlation for the normalized values was very good for the size classes A and B (x2=0.93 and x2=0.90). For the classes C to F, the correlation is low as the frequency of the events depends mostly on the presence of tall rock columns. The Magnitude-Frequency relationship follows a power-law with exponent -0.70.

Conclusions: The methodology which was developed for the calculation of overhang areas can efficiently provide the area of numerous overhangs where the manual calculation would be tedious. For the 7 analyzed sections, with rockfalls up to a few thousands m3, the Magnitude-Frequency relationship follows a power-law with exponent -0.70, which is consistent with the exponent indicated by Hungr et al. (1999) for rockfalls up to 104 m3. The normalized frequency per linear meter, for all events, was indicated to be best correlated with the normalized sum of overhangs area.

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ROCK-TOPPLING AND ROCKFALL RISK ASSESSMENT IN AREAS OF CANYONS: THE FATAL EVENT OF JANUARY 2022 IN CAPITÓLIO, BRAZIL

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The fatal rock-toppling event that occurred in January 8, 2022, in Capitólio (Minas Gerais, Brazil) highlighted the importance of the assessment of geological and hydrological risks in tourist areas where geodiversity is the main attraction. Tourism in natural areas, or Geoturism, has increased in recent years in Brazil, mostly in a disorderly manner, without a proper assessment of the potential geological hazards that visitors and workers can be exposed to, which can lead to catastrophic results. The aim of our study, therefore, is to assess the geological-geotechnical risk of four canyons located in the region of Capitólio, named: Mirante, where the fatal event occurred, Cascatinha, Tucanos and Cabritos. The rock-toppling event in the Mirante canyon caused 10 fatalities and was mainly triggered by rainfall, with a precipitation of 400 mm accumulated in the 30 days prior to the catastrophe, much higher than what is expected for summer months (ca. 280 mm). For the risk assessment, we first mapped the rockfall and rock topple hazard in the canyon, using the methodology developed by the Brazilian Geological Survey (SGB/CPRM). The method comprises (1) the identification, by means of topographical criteria, of the potential slope movements that can occur, (2) the delimitation of the projected behavior of the slope movement (i.e., areas of generation and impact), and (3) the qualification of its severity based on the physical characteristics of the terrain. Overall, the canyons are highly susceptible to toppling and fall of rock boulders, as well as rockslides, due mainly to the geological and structural characteristics of the rock mass, comprised of very fractured quartzite. The geological hazard mapping defined mainly areas of direct and indirect impacts, which practically cover the entire navigable area of three out of the four canyons (Mirante, Cascatinha and Tucanos). A qualitative analysis of the hazard, vulnerability and potential harm was conducted in the risk assessment for the area inside the canyons, with three classes of risk: Very High, High and Medium. As the analyzed canyons do not have fixed infrastructure and are only visited by small to medium-sized boats, at certain times of the day, the following measures are adopted to reduce and mitigate the associated risks: delimitation of the area where it is allowed to navigate within the canyon, keeping a safe distance from the slopes; suggestion of retention structures or removal of rock blocks/columns in more critical areas; reduction of visitors' exposure time to the existing geological hazard, as well as a reduction and control of the number of boats allowed in the canyon at the same time; definition of a geological-geotechnical monitoring and maintenance plan; mandatory use of personal protective equipment for visitors; orientation about the geological hazard and training of sailors and businessmen in the region, also on how to act in critical situations; and, finally, orientation of the visitors about the geological hazards prior to their trip to the canyons.

Keywords: Risk assessment, Landslides, Hazard mapping, Geoturism, Natural disasters

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ROCKFALL CHARACTERIZATION AND RISK EVALUATION BEFORE AND AFTER APPLYING MITIGATION MEASURES ALONG A MAN-MADE TRENCH OF THE BARI-TARANTO RAILWAY (APULIA, ITALY)

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Purpose: This study aims to set a life risk for exposures of single/multiple passengers, related to rockfalls occurring along a man-made trench, dig in the early ‘90s in highly fractured limestone to accommodate the Bari-Taranto railway (called “TR04”). A residual life risk is computed after designing mitigation measures. The two scenarios were compared to various thresholds in technical literature and standards to check design compliance to risk reduction.

Methods: The railway runs in the Murge plateau (Apulia, IT). The man-made trench was dug into the Mesozoic limestone “Calcare di Bari”. The trench walls are rarely protected by metallic nets reinforced with steel ropes and spikes and have slopes around 70°, separated by one or two intermediate banks with a width of approximately 2.5m, depending on the overall height. There’s a basal 1m-height wall + ditch system, that demonstrated a good barrier to prevent the main part of rockfalls from reaching the platform.

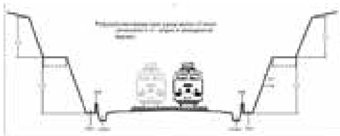


Fig. 1: typical trench geometry

The limestone have been characterized with traditional geomechanical and drone surveys to get appropriate design input, moreover all the major fallen volumes have been classified. Rock/debris slides were recognized, occurring within highly weathered/fractured or karsified zones, with higher volumes (up to 3-4m3) but not capable to reach the platform. A second type involves presumably a single block, generally with a volume not exceeding 0.125m3, but potentially capable to reach the platform.

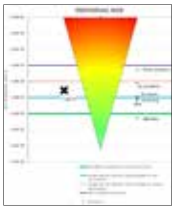
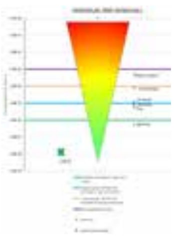
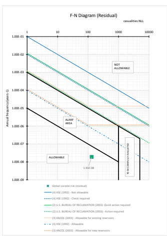


Fig. 2: Rock/debris slides and block fall

Fig. 3: Individual and societal risk

The life risk was assessed through the Australian Geomechanics Society’s method (2000). The main input parameters consist of the temporal and spatial probabilities of occurrence of an event and the vulnerability (passenger life). As regards the temporal probability of occurrence, no records were available about past falls; reference was made to available experiences about other limestone slopes. Thresholds of the block(s) size above which there’s actually a danger for a train allow to find the volume range to be analyzed. The spatial probability have been assessed through the 3D-modelling Rockyfor3D®.





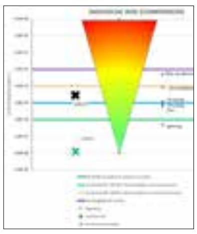


Fig. 4: Individual and societal risk (residual)

Fig. 4: Individual and societal risk (comparison to residual).

After design of mitigation measures, a probabilistic analysis of factor of safety has been introduced to get the residual risk.

Results: The comparison between initial and residual risk confirms that both individual and societal risk have been significantly lowered by mitigation measures with respect to international thresholds.

Conclusions: The proposed approach, known in technical literature, demonstrates its flexibility. Input can be critically deployed from technical literature, in order to find initial risk conditions and check effectiveness of mitigation measures against the instability. Risk variation is a crucial matter for the designer, who has to be deeply aware about the contribution to the stability of each single variable in a probabilistic meaning. That is a matter which is going to be more developed and will be increasingly required by public and private authorities.

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ROCKFALL HAZARD EVALUATION OF A HIMALAYAN ROAD-CUT SLOPE IN INDIA

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Rockfall is a natural mass-wasting process that involves the dislodging and rapid downslope movement of individual rocks and rock masses that may cause losses of life and property as well as economic loss. In the present study, a methodology has been proposed for rockfall hazard evaluation for a Himalayan road-cut slope, located along NH-58 near Shivpuri in Tehri Garhwal district of Uttarakhand, India. An existing road-cut rockfall potential slope, in the vicinity of the Shivpuri township, has been analysed using RS2 and RocFall program for stability assessment as well as to identify the rockfall initiation zone. The rockfall trajectory path has been observed through rockfall simulation and also the striking location of the falling block has been identified. Rockfall simulation was performed to evaluate maximum run-out distance, bounce height, total kinetic energy and translational velocity. Finite element method has been used for slope stability assessment by using RS2. The results reveal that this road-cut slope is partially stable with a FOS 1.09 under dry condition. The result of rockfall simulation shows that the falling blocks can reach to the road level and accumulate at road with approximate maximum run-out distance, bounce height, total kinetic energy, and translational velocity of 31.9 m, 3.1 m, 137.3 kJ, and 16.63 m/s, respectively. On the basis of result, it is concluded that in case of a rockfall event in future, the falling rock block is a risk to the vehicular traffic on this road. To minimize the risk, proper protection measures need to be designed and implemented at this site. This type of study is helpful to design the location and capacity of the protection barrier in order to minimize the risks.

Keyword: Rockfall Hazard, Slope Stability, Rockfall Simulation, Indian Himalayas

ROCKFALL SUSCEPTIBILITY ASSESSMENT ON ROCK WALL EQUIPPED FOR SPORT CLIMBING: A CASE STUDY FROM ITALY

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Purpose: In the last three years, the Italian Federation of Sport Climbing (FASI) has registered (in Italy) more than 35.000 competitive and non-competitive climbers in 2021 and more than 65.000 in 2022. These values represent the indoor presences, it follows that outdoor presences will be of a similar order of magnitude. Outdoor sport climbing activities could become a high-exposure-to-hazard activity if involved climbers are not aware of the potential instability processes that can occur on the climbed rock wall. To the best of the authors' knowledge, no type of detailed training or learning courses about rock fall hazard awareness are available (or provided by climbing organizations) for sport climbers that climb outdoor on real rock slopes. The practitioners are represented by beginner climbers, alpine guides, experienced and trained athletes, and bolters. Until today, due to the low number of practitioners and to the difficulties involved in such topic, i.e. rockfall hazard assessment, the issues linked to outdoor sport climbing has not been discussed so much in literature. This gap has led to potential hazardous situations; a lot of inexperienced and not trained practitioners (mainly beginners) want to climb outdoor, on real rock slopes, without any kind of knowledge and awareness about the potential instability mechanisms, follow that exposition to accidents are growing worldwide. This situation has motivated the authors to propose an index to quantify the rockfall hazard associated to each sport climbing routes: the Route Stability Index (RSI).

Methods: To evaluate the rock fall susceptibility values, two main close-range survey methods were used: terrestrial laser scanner (TLS) and unmanned aerial vehicle digital photogrammetry (UAV-DP). Following the suggestions of the International Society for Rock Mechanics (ISRM), a traditional field survey was carried out to obtain a quantitative description of the rock mass discontinuities. A kinematic analysis was carried out using the DiAna-k MATLAB routine. The susceptibility values of the following instability mechanisms were spatially mapped: wedge failure (WF), plane failure (PF), block toppling (BT), flexural toppling (FT) and free fall (FF).

Results: The proposed RSI was successfully applied to an equipped steep rock wall near Florence (Italy). Here, in 2014, there has been a rockfall of about 120 m3 that involved some of the equipped climbing routes. This case study allowed to calibrate the threshold of the proposed method for flysch-type outcrops.

Conclusions: The RSI aims to correlate and unify the geomechanical properties of the rock mass and the critical areas that a climbing route crosses returning a relative value of route hazard. To apply this procedure on other rock slopes equipped for sport climbing practice, further validation and calibration of the RSI are warranted if markedly different lithologies or sedimentary facies are involved respect to the showed case study.

AUTOMATIZATION OF KINEMATIC ANALYSIS: A CASE STUDY

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Purpose: This contribution presents an upgrade of the algorithm proposed by Taboni et al. (2022) for the automatic kinematic analysis of rock outcrops. The original version required initial processing of the discontinuities orientations to define discontinuity sets reference values, while this upgraded version directly considers the raw orientation of collected field data. New definitions of the output indexes are introduced to cope with the modified algorithm. A case study from the Upper Susa Valley (Italian Western Alps) is presented.

Methods: The upgraded algorithm still requires a Digital Surface Model (DSM) of the rockface: aspect and slope define the surface orientation in each raster cell. The algorithm performs Markland's tests for Planar Sliding, Wedge Sliding, Flexural Toppling, and Direct Toppling: in each cell, all orientations are tested. Then, for each type of movement, the percentage of tests where the movement is geometrically possible is calculated. Lastly, the tool normalizes those results over a constant (0.25) and multiplies the results to produce a global description of the rockface. The constant ensure the four movement types contribute equally. As this global index describes how active each cell of the DSM can potentially be, it was named Activity Index. The original approach was preserved and indicated as Deterministic, while the new one was called Raw Data. In the Upper Susa Valley (western Italian Alps), a rockface of Lower Triassic quartzite belonging to the Ambin Massif (Servizio Geologico d'Italia, 2002) was chosen as test site. On average, the investigated rockface dips at moderate angle toward SSW. The main foliation dips 30°-50° toward S-SSW. Fractures data were collected on several scanlines placed along the foliation strike: four main joint sets (Table 1) and several random joints were identified.

Table 1. Discontinuity sets in the test area.

Set	Dip	Dip Direction	Type
5	38	219	Foliation
K1	71	170	Joint
K2	61	83	Joint
K3	34	23	Joint
K4	65	333	Joint

Results: Results provided by both approaches (Figure 1) are similar, with the new one showing a more homogeneously active rockface; both approaches identify the highly active areas. The Raw Data approach is considered to depict more accurately the features of the rockface, given that it can take into account the variability of input data and random joints. The traditional stereoplot tests performed confirm the algorithm output.

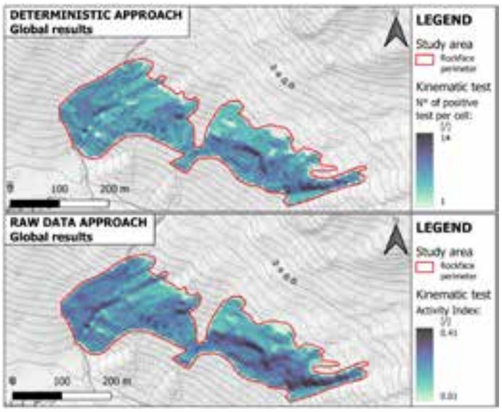

Fig. 1: Results of the Deterministic approach (above) and of the Row Data approach (below).

Conclusions: The upgraded algorithm provides a more realistic description of the kinematic possibility that a rockface is subject to instability phenomena, taking into account the natural variability of discontinuities orientations and presence of random joints, features not accounted for in the original. The new version requires a larger number of data to properly work, though; otherwise the orientation variability cannot be appreciated. Therefore, this approach is suggested only where a large unbiased orientation dataset is available. In the other cases, the Deterministic approach is still the best choice. The source code is available at: https://github.com/gessicaumili/AMTT2.0/tree/main

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SESSION 3.9

GEOTECHNICAL MITIGATION OF LANDSLIDE HAZARD THROUGH NATURE-BASED SOLUTIONS (NBS)

6th WORLD LANDSLIDE FORUM
2023 FLORENCE ITALY

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DESIGN OF NATURE-BASED SOLUTIONS FOR THE MITIGATION OF RISKS DUE TO SHALLOW LANDSLIDES

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Vegetation can mitigate the risks due to shallow landslides through various effects. Root reinforcement is recognized as one of the most important effects and the most suitable for quantitative implementation in the design of nature-based solutions using engineering standards. However, the practitioners are faced with a lack of information regarding methods to quantify root reinforcement and its implementation in the design of bioengineering measures. In many cases, this lack of information leads to large discrepancies between the approaches used for the design of technical or bioengineering mitigation's measures, resulting in difficulties to compare and accept different approaches for risk's mitigation. In the case of slope stability, the Eurocode 7 is the standard recognized for the design of stabilization measures in several countries.

In this contribution we analyze root reinforcement mechanisms and introduce a design approach of nature-based solutions for the mitigation of risks due to shallow landslides, within the framework of engineering standards used for the design of temporal and permanent technical measured.

Considering a case study in Switzerland, we illustrate how the planning and design of nature-based solution can be improved by considering the characteristics of the shallow landslides and the temporal dynamic of vegetation growth.

In the results we show how using appropriate partial safety factors for root reinforcement and a temporal dynamic model of the vegetation, it is possible to design nature-based solutions and compare them to other types of technical measures. Moreover, we discuss how bioengineering measures can be combined with temporal sustainable technical solutions to optimize the long-term mitigation of risks.

COMMUNITY LED NATURE-BASED SOLUTIONS: A SUSTAINABLE LANDSLIDE RISK MANAGEMENT PRACTICE

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Purpose: Landslides are one of the major hazards observed in hill country districts of Sri Lanka. Majority of landslide risk management practices adopted in the country are heavily dependent on grey solutions, which consist of conventional engineering techniques. Such measures are significantly expensive and they are better suited for implementation in the areas, where there is a high risk of landslides in order to protect human lives and assets. For areas, with the medium risk of landslides, grey solutions do not necessarily be deployed as there will be cost effective, sustainable and environmentally friendly landslide risk management techniques are available, which will also provide better returns on the investment. The Nature-based Solutions (NbS) fit in well into this concept, which is highlighted in the Sendai Framework for Disaster Risk Reduction (SFDRR) 2015-2030, as an effective tool and approach to reduce disaster risk, adapt to climate change and strengthen community resilience. This study attempted to demonstrate the vital role that NbS could play in formulating innovative, cost-effective, community-led risk management approaches for medium-risk landslide areas.

Methods: Quantitative and qualitative research coupled with literature surveys were engaged in the study. Community consultations in the medium landslide risk areas were conducted in order to obtain peoples perspective on the use of nature-based solutions and also to identify the ancient practices used by them to mitigate landslide risk.

Results: Plant species play an important role in nature-based solutions depending on the agro-ecological zone, where landslide risk is mitigating. Moreover, the ancient civilization practices found in the country such as Kandyan (upcountry) Home Gardens, have had positive contributions towards maintenance of slope stability, offering economic benefits to communities concurrently. Four core principles were identified for successful implementation of community led nature-based solutions (ClNbS). Namely, (1) ClNbS are user friendly (2) ClNbS are cost efficient (3) ClNbS suit the site-specific context and (4) ClNbS offer multiple benefits. Based on these four principles, different types of NbS such as live staking, vegetated crib walls, live slope grating etc. were introduced to four selected medium landslide risk sites with community participation and leadership. Plant species were selected after assessing their bioengineering characteristics in combination with ecological significance and economic importance. For instance, the economic benefits offered by the plant species could create new sources of income for vulnerable local communities, there by uplifting their socioeconomic conditions. Hence, the vulnerable communities are seen encouraged to take the lead in implementing and maintaining the solutions for protecting themselves and their assets from the landslide hazard.

Conclusions: The study revealed that NbS can be very effective as a long-term community led solution for landslide risk mitigation, while also offering other multiple benefits such as sustainable livelihoods, improved ecosystem services and overall enhancement of aesthetic appearance of the area.

DO WELL-STRUCTURED FORESTS PROTECT BETTER AGAINST SHALLOW LANDSLIDES?

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Purpose: The potential of vegetation and, particularly, forests to stabilise slopes and protecting against shallow landslides has been long recognised. Accordingly, numerous efforts have been undertaken in the last decades to quantify the corresponding vegetation effects. Nevertheless, appropriate tools and information easy to apply in practice for sustainably maintain the protective potential of the forests are still lacking. We, therefore, present a practice-oriented approach based on structural forest characteristics.

Methods: Focusing on practitioners, we present a straightforward approach based on the well-known stand code to characterise the structure of forests regarding maintenance measures. The key parameters are canopy cover, layering, development, and mixture. For this purpose, we analysed shallow landslides (WSL landslide database) of the 2002 thunderstorm in the canton Appenzell Ausserrhoden (AR) We performed a Multi Factor Analysis (MFA), including stand code, soil type and topography (factorial) as well as friction, cohesion, fines, pores, water content, slope, and altitude (numerical). Resultant, we suggest threshold values for stand code and the slope angle αlim, distinguishing well- and poor-structured forests. Additionally, supporting geotechnical investigations were performed to classify the soils according to USCS.

Results and Conclusions: MFA explained ≈61% and 90% on the first two and four axes, respectively. Only one of 32 shallow landslides was triggered in a well-structured stand (Tab. 1), exactly at the slope angle threshold αlim=35° (Figure 1). This scientifically supports the hypothesis of the higher protection potential attributed to well-structured forests.

Layering		Development	
0xxx	unstocked	x0xx	unstocked
1xxx → [illegible]	one-layered	x1xx → [illegible]	young stand / thicket
2xxx → [illegible]	multi-layered	x2xx → [illegible]	pole wood
3xxx → [illegible]	well-structured	x3xx → [illegible]	tree wood I (BHD 20-35 cm)
		x4xx → [illegible]	tree wood II (BHD 35-50 cm)
		x5xx → [illegible]	tree wood III (BHD >50 cm)
		x6xx → [illegible]	well-structured
Mixture		**Canopy Cover (CC)**	
xx0x	unstocked	xxx0	unstocked
xx1x → [illegible]	>80% coniferous	xxx1 → [illegible]	dense (CC >90%)
xx2x → [illegible]	mixed stands	xxx2 → [illegible]	normal (CC >80%)
xx3x → [illegible]	>80% deciduous trees	xxx3 → [illegible]	loose (CC >60%)
		xxx4 → [illegible]	lacunose (CC >40%)
		xxx5 → [illegible]	sparse (CC <20%)

Table 1: Stand code with commonly used and adapted factor levels (black numbers). Grey: Unstocked areas, not considered in statistical analyses. Green: Factor levels for «optimum» protection after NaiS (Sustainability in Protection Forests). Brown: Factor levels with inadequateprotection. Olive: Factor levels depending on altitude zone and layering with «optimum» and inadequate protection, respectively.

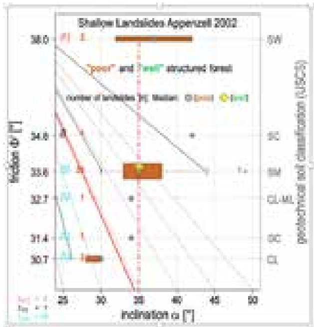

Fig. 1: Shallow landslides in the Swiss canton AR (2002) separated by geotechnical soil type (F=friction, I=intermediate, S=suction) depending on inclination α and forest structure (well, median♦; poor, median:●) with respective soil classification (USCS), corresponding friction angle Φ', and the inclination threshold $\alpha_{\lambda\iota\mu}$=35° (dot-dashed red line).

Our analysis reveals the dominance of suction (n = 29) over friction (n = 1) and intermediate soils (n = 2) and, thus, the importance of soil hydrology and evapotranspiration in terms of optimal protection against shallow landslides (Figure 1). We developed «Interactive 3D-Maps to assist forest management easily and practically. For this purpose, based on nationwide LiDAR data, we derived the forest stand code variables, terrain morphology, inclination, and a Topographic Wetness Index (TWI). These maps are provided within the «SHALLOW LANDSLIDES» application at «maps.wsl.ch» (Figure 2).

Fig. 2: a) Web-applications on «maps.wsl.ch»: Cartographic implementation platform for easily applying scientific results focussing on usability and practicability. b) SHALLOW LANDSLIDES: «Interactive 3D-Maps» on the effect of forest structure regarding the protection potential against shallow landslides.

THE ROLE OF LANDSLIDES IN INSTREAM LARGE WOOD RECRUITMENT: MODELLING TOOLS FOR FOREST MANAGEMENT ALONG CHANNELS

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Purpose: Shallow landslides are a recurring process that in alpine catchments may cause the mobilization and recruitment of huge amount of large wood (LW), leading to on-site and off-site hazards. Because plant roots may significantly increase the stability of vegetated slopes, forests can be considered an alternative protection against landslides with respect to other civil engineering measures. However, because forests are the source of LW, an accurate evaluation of the role of forest as protective measures or source of risk need to be carried out for the prioritization and planning of silvicultural measures. Root reinforcement effectiveness depends on many factors such as roots density, soil properties, and soil thickness, which implies that some vegetated areas have a more significant effect than others in mitigating shallow landslides. Moreover, the potential of a shallow landslide to recruit wood pieces and the capacity of a stream to transport them depend on multiple characteristics of the studied forest and catchment area, such as the volume of potential LW and the river geometry.

Methods: In this work, we present the application of SlideforMAP, a physically based probabilistic model for shallow landslides, combined with the model BankforMAP, a physically based probabilistic model for hydraulic bank erosion and LW transport, for the prioritization of silviculture measures along channels aiming to mitigate risks. SlideforMAP simulates expected precipitation-triggered shallow landslides by analyzing slope stability and takes the spatial distribution of lateral and basal root reinforcement into account. In this study, these models are used to quantify the protection effect of the forest against shallow landslides and the amount of LW mobilized from the slopes. In addition, we propose a methodology for using this model to quantify the volume of recruited and transported LW considering different triggering event and vegetation scenarios. Furthermore, we propose an approach for assessing the risk related to LW and its spatial distribution in a catchment.

Results: These tools and methods have been tested in a catchment of 29 km2 in Switzerland, allowing the identification of forested areas with high protection effect, the estimation of the volume of LW expected to be supplied by shallow landslides, as well as the volume of wood transported by the stream considering different triggering event and vegetation scenarios. These results were then used to assign spatially-distributed values of risk to LW.

Conclusions: Altogether, these results highlight areas where the forest has an important protection effect and where it might pose a risk. Ultimately, the results of this study can be used by decision makers to prioritize the role of protection forest in a catchment and to support the definition of silvicultural measures to mitigate the risks due to LW transport.

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NATURE-BASED SOLUTIONS FOR LANDSLIDE RISK MITIGATION IN ITALY: STATISTICS FROM RENDIS, THE MONITORING DATABASE OF THE ITALIAN INSTITUTE FOR ENVIRONMENTAL PROTECTION AND RESEARCH (ISPRA)

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Purpose: ISPRA has developed the National Repository of hydrogeological risk mitigation measures (ReNDiS), a web-GIS open data platform funded by the Italian Ministry of the Environment and Energy Security, to control the implementation of such kind of measures and manage the evaluation of funding requests coming from all the Italian Regions, from 1999 onwards. In the ReNDis database, information is organized by single “mitigation measures” for which the project stages, work typology and accounting data are collected and stored. The database has a section dedicated to nature-based solutions -NbS- (http://www.rendis.isprambiente.it/INventario/), in which measures for hydro-geological risk mitigation implementing those techniques (among other works) are geo-referenced (if the location is not specified by the user, the centroid of the Municipality is automatically indicated). Given the high socio-economic impact of landslides and the importance of the ecological and sustainable transition, the aim of the work is to analyse the frequency and types of NbS most frequently used among the measures for the mitigation of landslide risk in Italy.

Methods: Data for the statistics were obtained from the database. Geographically-based statistics were conducted in QGIS software.

Results: About 12 thousand mitigation measures have been already reported in the database, corresponding to over EUR 29 billion of funds. Among these entries, 61% are related to landslide risk mitigation. 17% of such measures implement NbS, while this amount is reduced to 11.8% in the case of hydraulic risk mitigation. The 30% of the measures implementing NbS fall into Natura 2000 (adopting a buffer radius of 500 m), the network of protected areas of the European Union (Figure 1). The most adopted NbS works among the landslide risk mitigation measures are shown in Figure 2a. Vegetation cutting and selective deforestation are the most used techniques in areas where the overloading of vegetation has a destabilising action that prevails over root reinforcement. In most of the cases, vegetation’s reinforcement is combined with structures or reinforcements made by biodegradable materials such as wood (edging, palisades, gutters), bio-mats, bio-nets and bio-felt. On the other hand, the typical traditional works (Figure 2b) include concrete piles and walls, steel meshes, barriers and reinforcement, and drainage systems. NbS are a conspicuous amount of the whole typologies of works for landslide risk mitigation, although they are often used in combination with more 'traditional' engineering works.

Conclusions: Nature-based solutions often offer an improvement in soil resistance over time and need low maintenance. They are more economical and cover larger areas than traditional works such as retaining walls or piles, thus reducing surface landslide phenomena such as earthflows and erosion to a greater extent. Given the landscape, cultural, economic and sustainability interests involved, the monitoring of nature-based solutions through the ReNDiS database is a fundamental tool for planning new landslide mitigation works throughout Italy.

Fig. 1 Measures implementing NbS (points) and Natura 2000 protected areas (polygons). SIC: Site of Community importance, ZPS: Special Protection Area, ZSC: Special Area of Conservation.

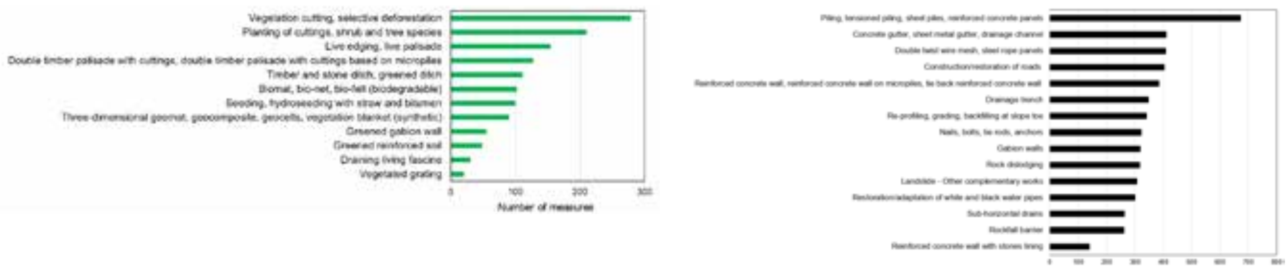

Fig. 2. Most used works with (green) and without (black) NbS

GEOTECHNICAL ANALYSIS OF THE TEMPORAL VARIABILITY OF THE PERFORMANCE OF A "COMBINED" GREEN-GREY SLOPE STABILIZATION INTERVENTION

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The sustainable mitigation of landslide hazard is an ethical and technical goal of increasing global relevance. "Conventional" geotechnical stabilization solutions may meet performance criteria but are scarcely sustainable. Nature-based solutions (NBS) use living plants and locally available materials to increase the engineering performance of geo-structures while fostering their biodiversity. The domain of application of NBS is limited to quasi-surficial instability phenomena, since the root systems which provide mechanical resistance develop mainly at surficial depths. "Combined" solutions involving the concurrence and functional synergy between grey and green solutions may ensure the simultaneous attainment of stabilizing performance and sustainability-related criteria. This abstract outlines the main features of a case-study of slope stabilization using a combined solution implemented at the rural site of Montisoni in the hills surrounding Florence. Details can be found in Boni (2022), which also provides the outputs of a comparative analysis of this solution with grey-only and green-only solutions. The rainfall-induced landslide is classifiable as a compound phenomenon. Slope stabilization involved the design and implementation of the following technical sequence (see Figure 1): (1) reinstatement of the road embankment; (2) realization of water drainage measures; (3) realization of 11 steel minipiles; (4) reprofiling of the slope using two orders of double piles and wooden crib walls filled with excavated soil and draining materials; (5) greening of the slope using native grasses and legumes; and (6) construction of retaining wall. Geotechnical analysis must account for the biological and physical processes which modify the mechanical properties of NBS. Slope stability was assessed through limit equilibrium methods using the SSAP software (Borselli 2022). Morgenstern & Price's method was implemented with "Random Search" (RS) random surface generation. Samples of 10,000 locally concave-convex composite random surfaces were generated through Monte Carlo Simulation for three temporal scenarios: "C2.0" (time of construction), "C2.1" (10 years after construction), and "C2.2" (25 years after construction). The minimum factor of safety FS, corresponding to the most critical rupture surface, was recorded for each scenario. Figure 2 plots the spatial variability of the average values (for the 10,000 random surfaces) provided by the SSAP software. Visual inspection confirms the beneficial effect of root development over time. Such effect prevails over the one brought by the mechanical deterioration of the wooden double piles and crib walls. Figure 3 shows the increase in the critical FS over time attesting to the increased temporal effectiveness of the combined solution.

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Fig. 1. Stabilization of the Montisoni landslide using a combined solution: (a) phases 1-2; (b) phase 3; (c) and (d) phase 4; (e) phases 5; (f) phase 6.

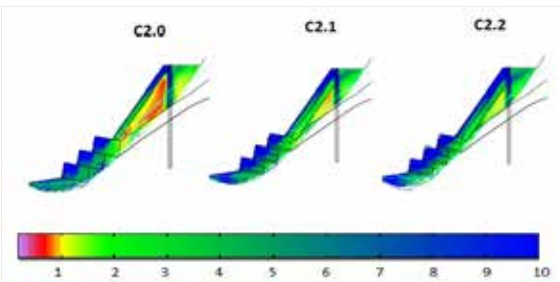

Fig. 2. Temporal and spatial variability of average FS.

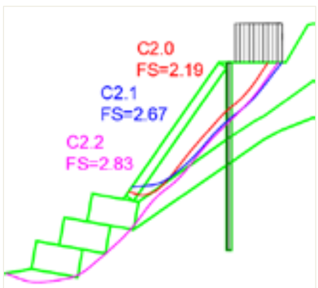

Fig. 3. Temporal evolution of critical FS and corresponding surface

STABILISING A COARSE PYROCLASTIC SOIL WITH GUAR GUM AS A FLOWSLIDE RISK MITIGATION MEASURE: A PRELIMINARY EXPERIMENTAL INVESTIGATION AT LABORATORY SCALE

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Purpose: Flow-like landslides in the Campania region involve pyroclastic soils often in partially saturated conditions [1]. This preliminary study explores using guar gum to stabilise coarse pyroclastic silty sand collected from Mt. Faito (Campania) [2] and hence mitigate flow-like landslides risks. Guar gum is a polysaccharide extracted from the endosperm of cluster beans belonging to Leguminosae plant family. It was selected because it is an environmentally friendly stabiliser compared with cement and petroleum-based polymers [3].

Methods: The effect of guar gum stabilisation on the shear strength of a coarse pyroclastic silty-sand is investigated via saturated direct shear tests. Samples were prepared by mixing 120 grams of dry soil at a liquid content of 16.7% and guar gum concentration of 63.8 g/l, corresponding to 1.2 grams of guar gum (i.e., 1% of the dry mass of the soil) dissolved in 18.8 grams of water. The sample preparation method aims to mimic the wet-mixing procedure usually adopted by ground improvement contractors. After mixing, the moist soil was stored in zip-lock plastic bags for 7 days and then compacted at the dry unit weight of 11.1 kN/m3, which is slightly higher than the dry unit weight of 10.1 kN/m3 determined by Forte et al. [2] on several undisturbed samples of the same soil. Saturated direct shear tests were performed at the five constant vertical effective stresses, σ'v of 15, 30, 50, 100 and 150 kPa.

Results: Figure 1 shows the shear strength, τ of guar gum stabilized soil samples against σ'v as measured in the present experimental campaign together with results obtained by Forte et al. [2] on unstabilised material. The preliminary results in Figure 1 suggest that the guar gum stabilisation marginally reduces the soil friction angle. This is because the soil grains of the stabilised samples are coated with a biopolymeric hydrogel that decreases the friction at the inter-particle contacts, also shown by Bagheri et al. [4]. However, guar gum stabilisation generates a cohesive component of the soil shear strength, which is absent in the unstabilised material.

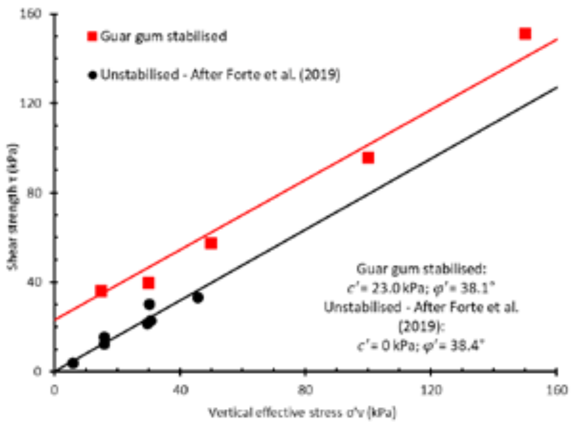

Fig. 1. Shear strength of guar gum stabilised and unstabilised pyroclastic silty-sand samples.

Conclusions: This paper presented preliminary experimental work on the use of guar gum to stabilise pyroclastic silty-sand often affected by flow-like landslide phenomena. Saturated direct shear tests were performed to measure the effect of guar gum stabilisation in comparison to the behaviour of the same unstabilised soil. Results show that biopolymer stabilisation induces a small reduction of the friction angle and a considerable increase in cohesion, thus suggesting that this stabilisation technique may be considered as a potential mitigation measure against shallow flow-like landslides. Future work should be directed towards the extension of the present experimental campaign to other laboratory tests (e.g., triaxial tests) and upscaling the proposed stabilisation method to real slopes.

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AMELIORATION OF BAUXITE RESIUDE TO IMPROVE SOIL CHARACTERISTICS TO REDUCE EROSION

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Purpose: The amelioration of Bauxite residue (BR) followed by the establishment of vegetation is vital to restore the ecosystem in disposal areas, while simultaneously improving soil characteristics and reducing wind and water erosion.

Methods: This research investigates how seeds of ryegrass (Lolium perenne) grow in five different combinations of ameliorated bauxite residue from Brazil using visual observation and quantitative and qualitative 3D image analysis of micro-CT scans. Bauxite residue was mixed with either gypsum (G), organic food (O) waste, and acai (A) waste (Euterpe oleracea) in different percentages (i. BR=90%, G=10%; ii. BR=90%, O=5%, G=5%; iii. BR=85%, O=5%, G=10%; iv. BR=90% A=5%; G=5% and v. BR=85%, A=5%, G=10%). Cylinders of bauxite mixture and ryegrass seeds were prepared at laboratory, and micro-CT scanned at different time steps (before seeding, after seeding, 2 weeks and 4 weeks after seeding). Image analysis of CT-scans at 2 and 4 weeks after seeding allowed to calculate the root morphological parameters commonly used in geotechnical engineering such as Root Volume Density (RVD), Root Depth (RD), and Root Area Ratio (RAR).

Results: We systematically compared the calculated root morphological features to determine which ameliorated bauxite mixture enhance the growth of ryegrass. Visual observation of the grass suggested that the best amelioration was gypsum at 10%, since ryegrass developed rather quickly. This was confirmed by quantitative image-based results, indicating that this amelioration allowed the grass to thrive and to develop a deeper and stabilizing root system after two and four weeks after planting

Conclusions: This research highlights the importance of using gypsum for amelioration and revegetation of mine bauxite residual soil.

APPLICATION OF NATURE-BASED SOLUTIONS IN MITIGATION OF HILLSIDE UNSTABLE ROAD CUTS IN SRI LANKA

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Purpose: Nature - Based Solutions (NBS) are actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (Cohen-Shacham et al., 2016). The importance of NBS is highlighted in international agreements such as the Sendai Framework for Disaster Risk Reduction 2015–2030 as promising strategies to reduce disaster risk, adapt to climatic change, and strengthen community resilience. Roadside unstable slopes of Sri Lanka are a result of vertical slope cuts made in road construction and are exposed to significant landslide risk during the monsoon season. Eighteen unstable slopes in Kandy district along the Kandy-Mahiyangana Road were mitigated under Climate Resilience Improvement Project with financial assistance from the World Bank and was implemented by Road Development Authority and National Building Research Organisation (NBRO). The NBRO involved in investigations, designing, and supervising slope stabilization as the mandated landslide assessment and mitigation entity in Sri Lanka. This paper highlights the effective use of NBS in this landslide disaster risk reduction project.

Methods: The sites were in the central fragile area of the country with high erosion susceptibility and reservoir siltation. The mitigation designs were hybrid-type with both structural engineering mitigations and NBS. NBS were chosen considering the critical habitat conditions, susceptibility to slope erosion, ecosystem functionality, adaptability to co-exist with the existing environment, and other co-benefit functions of NBS. An array of on-site environmental management and bio-engineering mitigation were used as NBS. Site-specific environmental and social assessments to understand site-specific nature-based functions and requirements, and rationalized selection of NBS by professional judgment were used in the mitigation and were included in the environmental management plan to be followed by the contractor during the mitigation.

Results: Slope modifications with stable slope gradients, drainage improvement, and soil reinforcement (soil nailing) were the structural engineering measures used. The key on-site environmental management measures used during construction were; (i) minimizing the extent of vegetation clearance by demarcating allowable areas to be cleared, (ii) protecting the sensitive plants and critical habitats in forest reservations, (iii) introducing connective vegetation strips and animal trials on the steep slope sections at critical habitats, (iv) onsite management of sediment and debris to prevent contamination of runoff and siltation of reservoirs and, (v) restrict disposing of all debris and any left earth to reservations/stream banks. Hydroseeding with endemic or native plant species was the bioengineering measure used for erosion control and slope protection. Bio-degradable geotextiles were the other bioengineering measure used to cover soil surface and reduce erosion from rainfall impact. They also supported faster root-soil matrix formation to promote seed germination and protect seeds along slopes in the initial stage of vegetation establishment.

Conclusions: This study portrays the application of NBS at every stage of the project cycle to ensure long-term disaster resilience and environmental sustainability.

Keywords: Nature-Based Solutions, hybrid, Disaster resilience, Environmental Sustainability

NATURE-BASED SOLUTIONS IN THE PYRENEES DURING THE H2020 'PHUSICOS' PROJECT

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Purpose: The H2020 project Phusicos (2018-2023) designs and implements Nature-Based Solutions (NBS) at demonstrator case sites in rural areas of Norway, Italy, and in the French and Spanish Pyrenees. The purpose of Phusicos is to demonstrate that nature-based and nature-inspired solutions for reducing the impact of extreme weather events in rural mountain landscapes, are technically viable, socially acceptable, cost-effective and implementable at the regional scale. Phusicos demonstrator sites comprise NBS for flooding, erosion, run-off from farmland, snow avalanches, rockfall, slope instability, and debris flows. This presentation covers three locations in the Pyrenees, where NBS to reduce risk from slope instability, rockfall, and debris flows are implemented.

Methods: Rockfall poses a severe hazard at two locations along the important road A-136 / RD-934 between France and Spain. At St. Elena, Spain, rocks are released by erosion of a slope in a thick till deposit. The implemented NBS consists of vegetated terraces, built up by a dry masonry wall and wooden gabions filled with the local sediment. At the other location, Artouste, France, rockfalls are released from exposed ledges and from loose blocks in the till surface. The measures here consist of wooden stabilising and retaining structures for each individual ledge or block. These solutions are also tested at newly established test facilities in Spain. The third location is near the Spanish village Erill-la-Vall, where debris flows from a >50m thick till deposit pose the threat. Several gullies feed the main debris flow path towards the village during periods of extreme precipitation. The implemented solution is a series of terraces, built up by local rocks and whole-log gabions in the lower parts of the gullies. These will prevent deepening of the erosional base and form increased rugosity in the debris flow paths.

Results: Monitoring of the effects of the implemented NBS is an important part of Phusicos. However, as the implementation of the solutions has been completed late in the project, it is still too early to report concrete effects of the implemented measures. Baseline data have been acquired from all the sites, but the only long series of data is from the debris flow site at Erill-La-Vall, where in-situ borehole (piezometer) data show two processes: a deep-seated (15-20 m) failure level, which reacts up to two weeks after a period of heavy rain, and shallow erosion, which reacts almost immediately as a direct response to heavy precipitation.

Conclusions: The NBS described here all have large upscaling potential, as there are numerous locations in the Pyrenees and elsewhere with similar problems. 'Living-Lab' processes with stakeholders have helped overcoming challenges related to land ownership issues and permissions to operate, e.g., in national parks. Literature on barriers for NBS frequently points at the lack of evidence for the functionality of NBS for disaster risk reduction as a main barrier for their implementation. Therefore, continued Phusicos work in the Pyrenees will focus on monitoring of the implemented measures, both the resilience aspect and the NBS's co-benefits, adding to such an evidence base.

SESSION 4.8

LANDSLIDE IMPACTS, VULNERABILITY AND QUANTITATIVE RISK ASSESSMENTS OF PEOPLE, COMMUNITIES, STRUCTURES, AND INFRASTRUCTURE (part I)

EFFECTS OF VERY SLOW MOVING GRAITATIVE DEFORMATIONS ON CIVIL INFRASTRUCTURES: THE CASE STUDY OF ISCHIA DEL BASENTO

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Purpose: Slow and very slow moving landslides and deep seated gravitational slow deformations are quite common, particularly in young geological regions, recently involved by orogenetic processes like a large part of Italian territory. These are gravitative phenomena, often large or very large, characterized by slow continuous movements, with displacements rates lower than few millimeters per year. These landslides can be considered apparently of no interest, when no structures and infrastructures exist; however if they involve infrastructures like bridges or tunnels or road or railway embankments, the cumulative displacements may seriously damage them. In Italy, there are a lot of slow moving landslides, which are often unknown, these over long time may causes serious damages to infrastructures. These landslides are unfortunately discovered when they damage infrastructures, causing, sometimes, unreversible damages, which compromise the use of the involved infrastructures. This work focuses on the case of the landslide of Ischia del Basento, in south Italy, at the toe of the right flank of river Basento valley close to the railway station of Ferrandina, in south Italy. In this area, about 20 years ago, an old masonry bridge crossing Basento river collapsed and a tunnel of an important national road dug at the toe of the slope is continuously subject to severe deformations. This case history give evidence of the risk related to slow moving slopes both for bridges than for tunnels.

Methods: The investigated area involves the toe of a moderately steep slope, made of clayey silts and clays. The slope is subject to very slow movements; it is mostly covered by vegetation, without large artificial structures, except for a tunnel crossing its toe. A geometrical of the morphologies of the slope is attempted using a LiDAR-based DTM and cross sections showing the relation between the slope and the infrastructures: the bridge and the tunnel. Finally, a critical investigation on the impacts on infrastructures using remote sensing techniques and particularly interferometric data in attempted.

Results: This case study is very interesting since the tunnel, made of two barrels, at the toe of the landslide, due to the continuous displacements, is under a sort of permanent maintenance, since it is continuously damaged. In addition, the bridge at the toe of the landslide collapsed, see figure 1. The collapse, according to the official interpretation is due to the aging degradation of the bridge, about 60 years, and to the effect of some floods. Here it is proposed a new interpretation of the collapse, that according to the developed analysis is essentially due to the continuous pushing effects of the backward slope.

Conclusions: The investigated site is a really interesting case history showing how gravitative slope deformations can condition and damage the infrastructures at their toe over very long periods, not immediately evident, thus creating risk conditions.

Fig. 1: Evidences of the compression stresses, which caused the failure.

PRIORITIZING RAILWAY STRETCHES REQUIRING RISK MITIGATION MEASURES BASED ON THE INTEGRATED USE OF AIRBORNE LIDAR AND MOBILE MAPPING DATA: CASE STUDIES IN CENTRAL ITALY

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Purpose: Landslides originating in hilly and mountainous natural slopes can directly affect the railway corridors, in turn causing – often severe – indirect consequences to travelling persons (in terms of injuries and loss of life) and economic activities. This is the case of existing landslides, slowly moving on buried sliding surfaces, which may dislocate the railway platforms so isolating urbanized areas. First-time landslides, rapidly moving on channelized or open slopes, may generate detrimental effects too. Owing to the importance of the problem, activities must be carried out to properly predict the landslide occurrence and (eventually) prevent the related direct and indirect consequences to the exposed railway stretches. In this regard, qualitative risk-based approaches can be adopted to profitably tackle the problem under consideration at large scale (1:5,000 to 1:25,000), when many slopes are dealing with. These approaches includes the use of ranking matrices, as operated in the official practice in Italy within the so-called Hydro-geological Setting Plans - HSPs (Law 365/2000). In compliance with governmental requirements, four risk levels had to be considered by Authorities at that time in charge of the landslide risk analysis and zoning (i.e., River Basin Authorities and Regions). Independently of the adopted approach, all the produced risk zoning maps are unsuitable for: i) the prioritization of equally-classified at-risk areas/linear facilities requiring either non-structural or structural interventions and the related earmarking of financial resources, and ii) the selection of the most appropriate risk reduction strategy (including type, location and size of structural interventions, in the cases where they are required).

Methods: Considering the above shortcomings associated with the use of official risk zoning maps, this paper provides a procedure that – based on the geomorphological criteria adopted by former River Basin Authorities for qualitative landslide risk analyses and zoning – enhances the integrated use of airborne Light Detection and Ranging (LiDAR) and Mobile Mapping high-quality data to first identify the different landforms where landslide processes affecting natural slopes originate. A rating scheme is then devised.

Results: The proposed procedure made it possible to generate a geomorphological map at detailed scale (1:2,000) of landforms where landslides of a given intensity (in terms of maximum expected velocity) might occur and to estimate the number of persons at risk traveling on trains along the threatened railway stretches. Its applicability was tested in two case studies from central Italy, selected in territories managed by different former River Basin Authorities. The results obtained were summarized in a zoning map (at 1:10,000 scale) of priority railway stretches based on the total rating derived from the product of a score assigned to a given landform and the related number of persons at risk.

Conclusions: The results obtained allowed for the prioritization of the railways stretches requiring landslide risk mitigation measures. The latter may deal with prevention (e.g., stabilization) interventions in natural slopes where landslides might originate. Further developments will concern quantitative studies at detailed scale, namely the mandatory scale for a proper selection and design of the above interventions, including artificial slopes.

EFFECTS OF TUNNEL CONSTRUCTION IN LANDSLIDE-PRONE AREAS

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Purpose: Construction of roads and tunnels in mountainous areas encounters special challenges in how the construction can be carried out without causing significant environmental impacts. One such important impact is on slope stability, particularly in landslide-prone areas that have already undergone severe landslides. This is the challenge faced in planning for the extension by adding additional tunnel bores along the Eisenhower-Johnson Memorial Tunnel (EJMT) in Colorado, USA. The additional tunnels are needed to accommodate increased traffic through the Continental Divide along the I-70 highway, which connects the eastern front of Colorado to its western front and the state of Utah. Several major landslides have occurred around EJMT, and a major creeping slide endangers the existing roads and tunnels. The major concern is if and how additional tunnels and their locations can impact landslide potential along and in the vicinity of EJMT.

Methods: Deterministic and probabilistic numerical modeling of the interactions between new tunnel locations and slope stability along EJMT were performed. The modeling used classical two-dimensional slope stability analysis and a finite difference computer code to determine the optimal tunnel locations in EJMT without triggering new landslides due to the tunnel construction. The model geometries and soil stratigraphy were based on previous landslide evaluations of the area, and geotechnical properties were based on the design of the existing EJMT twin tunnel bores. Monte Carlo Simulations were carried out to relate the safety factor against landslides to the probability of failure.

Results: The deterministic slope stability analyses established that there is a minimum distance between a new dual-bore tunnel and the surface of the slope at which slope stability is virtually unaltered by the tunnel construction. Specifically, tunnel-slope interaction was minimized past a horizontal distance of 5.5 times the tunnel diameter from the slope surface. The probabilistic analyses showed that a horizontal distance of 5.5 times the tunnel diameter provides a factor of safety FS of 1.4, which is close to the accepted minimum value of 1.5 used in practice. In addition, the probability of failure Pf for this FS is less than the acceptable value of 10% used in practice.

Conclusions: The study showed that it is possible to construct new tunnel bores to expand the traffic capacity of existing tunnels without the new tunnels endangering slope stability above the tunnels. A minimum horizontal distance of the new tunnel location should be observed, which will provide an acceptable factor of safety and probability of failure.

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MULTI-SCENARIO APPROACH FOR CO-SEISMIC LANDSLIDE ASSESSMENTS ACROSS ROAD NETWORKS

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Purpose: Events such as the 2016 Kaikōura earthquake demonstrated the impacts of co-seismic landslides on New Zealand infrastructure networks and emphasized the importance of national-scale landslide assessments for the social and economic wellbeing. In order to better understand the exposure of earthquake triggered landslides across the New Zealand State Highway network, a geospatial landslide model is linked to a viewshed approach to predict the probability of road blockages caused by co-seismic landslides.

Methods: A New Zealand specific landslide model is used to calculate the landslide probability of approximately 500 actual and hypothetical earthquake scenarios. The estimates are linked to a viewshed approach, which aggregates the landslide probabilities across the area visible to a point along the State Highway network. The aggregated probability is used to predict whether a landslide enters a State Highway section during an earthquake. The overall hazard is measured by the number of scenarios that are expected to cause a road blockage. Compared to the assessment of a specific earthquake scenario or a specific return period, the multi-scenario approach helps to identify State Highways that might be affected by co-seismic landslides during a range of different earthquakes, hence, might lead to a recurrent disruption of transport services.

Results: The results are presented in a hazard map, highlighting State Highways that might be affected by multiple earthquakes. State Highway 1 and 2, which present critical links to metropolitan Wellington, lead to the highest number of scenarios that potentially result in road blockages. Given the large volume of daily traffic, a disruption of the network would severely impact the local community.

Conclusions: Linking a geospatial landslide model to a viewshed approach allows for the (rapid) calculation of the probability of landslide triggered road blockages. The results help identifying State Highway sections that are likely affected by a range of different earthquakes. Future research should look into combining the exposure results with indicators for network criticality (e.g., number of vehicles, or freight value) to better quantify the impact of road blockages caused by co-seismic landslides. The framework is adaptable to other infrastructure networks and can be used to support decision making processes regarding hazard mitigation or preparedness for future earthquakes.

ADVANCES IN THE USE OF REMOTE SENSING FOR ROAD MONITORING IN LANDSLIDE AREAS

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Purpose: Understanding the damage mechanism of road pavements and quantifying the movements affecting the infrastructure are major requirements to investigate road vulnerability to slow landslides. Remote Sensing techniques are helpful tools for rapidly monitoring road infrastructures in landslides areas. Interferometric Synthetic Aperture Radar (InSAR) is used to estimate the displacements of road pavements in wide areas due to slow landslides. Other technologies, as Unmanned Aerial Vehicles (UAV), have been introduced for detailed inspections of road pavement damage in landslide areas. Examples from ongoing research are presented here to discuss the current use of InSAR and UAV-based photogrammetry for road monitoring in slow landslide areas.

Methods: First, the use of InSAR to investigate the vulnerability of roads to slow landslides is presented. This approach proposed by Nappo et al. (2019) implies four main steps: i) identification of exposed element, ii) classification of damage severity via visual inspections, iii) quantification of landslide intensity (i.e., differential displacement) at damage locations using InSAR, and iv) analysis of cause-effect relationships between road damage and landslide intensity. The method is applied to a section of 17km of the state road SS177 in Calabria region (South Italy). The second case presents the method proposed by Nappo et al. (2021) to characterize road pavement damage in slow landslide areas using 2D and 3D photogrammetric products reconstructed from UAV images. The main steps are: i) data collection and processing via Structure from Motion, ii) detection of pavement unevenness and roughness using 3D point cloud, iii) damage detection on 2D orthophoto via computer vision algorithms, and iv) damage severity classification based on International Roughness Index (IRI). This procedure is applied to a segment of 110 m of the provincial road SP14 in Laino municipality (North Italy).

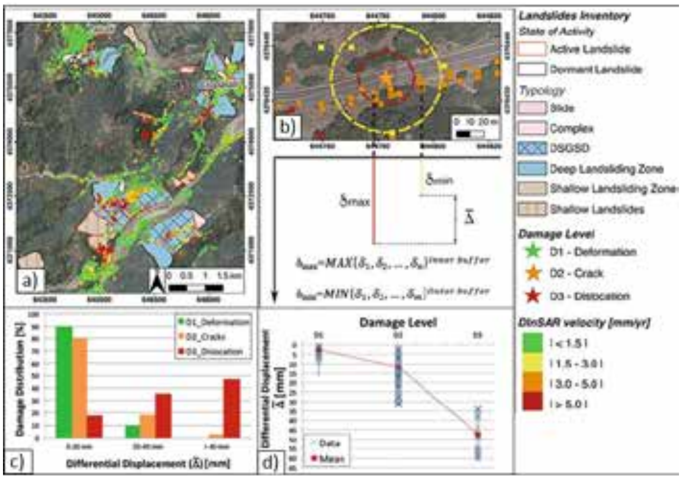

Fig. 1: SS177– Calabria. a) Identification of road exposed to slow landslides with overlapped InSAR acquisitions. b) Framework for computing the landslide differential displacements at each road damage location. c) Percentage distribution of road damage severity levels vs landslide intensity. d) Relationship between landslide intensity and road damage severity. Modified from Nappo et al., 2019.

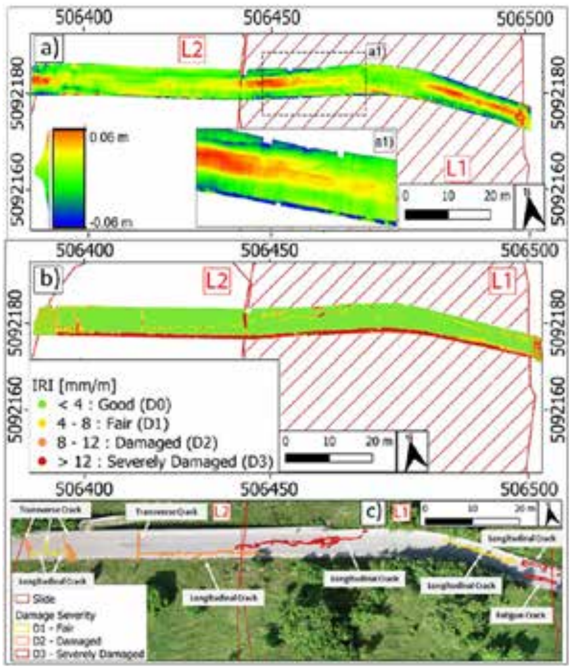

Fig. 2: SP14 – Laino. a) Detection of pavement unevenness intersecting the 3D point cloud with a reference planar surface. b) Automatic classification of 3D points in four levels according to the IRI. c) Severity classification of 2D pavement fractures based on IRI. Modified from Nappo et al., 2021.

Results: Figure 1 shows the use of InSAR to assess the vulnerability of SS177 to slow landslides. Figure 2 shows the application of UAV-based photogrammetry to detect and classify damage caused by slow landslides on SP14 pavement.

Conclusions: Current trends in using InSAR and UAV-based photogrammetry for road vulnerability assessment are presented here. The application to SS177 shows that InSAR is preferred for wide area analyses, given that the investigated road and slope orientation is compatible with the satellite acquisition geometry. The application to SP14 indicates that photogrammetric 2D and 3D products as reconstructed from UAV are suitable for measuring road pavement damage in landslide areas.

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MONITORING/SURVEYING DATA-BASED QUANTITATIVE RISK ASSESSMENT FOR A ROAD CROSSING A SLOW-MOVING LANDSLIDE-AFFECTED AREA

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Purpose: The study addresses the quantitative risk assessment of a state road crossing an area of southern Italy affected by slow-moving landslides, which in the last two decades have repeatedly caused damage of different severity level and some temporary traffic interruptions or limitation. For the purpose of a sustainable landslide risk management, a procedure based on multi-source monitoring/survey data exploitation was implemented. The availability of multi-temporal datasets allowed analyzing the relationship between the landslide kinematic features and the associated effects in terms of damage severity. This phase was propaedeutic to set up probabilistic consequence forecasting models (i.e. fragility and vulnerability curves) that were used to quantify economic losses for a fixed time scenario.

Methods: The analyses were carried out as follow-up of an ongoing research (Borrelli and Gullà 2017; Ferlisi et al., 2021). Specifically, multi-temporal and multi-source damage datasets were analyzed considering the visible effects on both the asphalt pavement and the retaining structures of the infrastructure with multi-source displacement monitoring data. Then, probabilistic forecasting tools were derived for the road stretch and were used for risk assessment.

Results: The exposed element is the state road SS660 (Figure 1) in Acri municipality (Calabria region, southern Italy), which crosses an area affected by three categories of landslides (shallow, medium-deep, and deep landslides) occurring in weathered crystalline rocks in turn located within a deep-seated gravitational slope deformation (DSGSD). The area has been studied and monitored in the past (Borrelli and Gullà 2017), so that a rich database consisting of primary geological-geomorphological and geotechnical data, conventional (i.e. GPS) and remote sensing (i.e. DInSAR) displacement data, in-situ and virtual (i.e. Google Street View images) damage survey results is available. The analyses allowed deriving i) an overview of the evolution of road damage, ii) the appropriate association of the cumulative landslide-induced displacements with the damage resulting from the interaction of the road with the unstable slopes, iii) the quantitative risk assessment of the road in terms of repair costs in a 3-year scenario.

Conclusions: Considering that the studied area resembles typical conditions of inner roads in hilly areas of southern Italy, the assessment of the economic losses induced by the slow-moving landslides - should no countermeasure or mitigation works be implemented within a reasonable time - can represent a valuable tool for decision makers to prioritize money allocation for risk mitigation actions for roads in similar geo-environmental contexts.

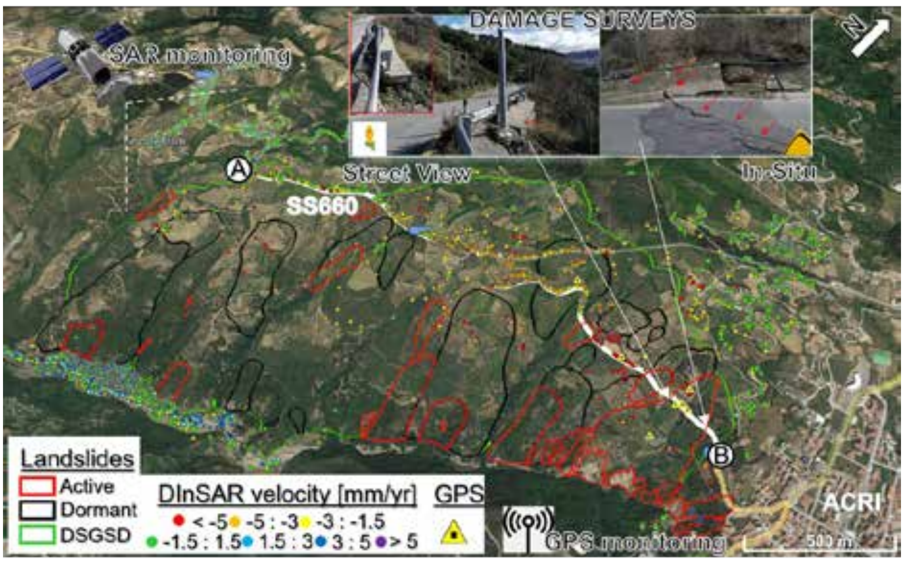

Fig. 1: Portion (A-B) of the state road SS660 (Acri municipality - Calabria region, southern Italy) analyzed with multi-source (ground-based GPS and remote-sensing DInSAR) displacements monitoring and multi-temporal (virtual and in-situ and damage surveys).

Funding: This research has been financially supported by MEFISTO project co-funded by the Italian Space Agency (ASI Contract n. 2021-10-UO).

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QUANTITATIVE RISK ASSESSMENT FOR THE A82 STRATEGIC ROAD IN GLEN COE, SCOTLAND

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Purpose: Glen Coe is one of the most iconic tourist attractions in Scotland (Figure 1). The A82 strategic road that runs through Glen Coe, linking Glasgow and Inverness, provides access to skiing, walking and climbing as well as being an important stop on tourist routes for both private parties and those who take organised tours. Two car parks that provide access to the Hidden Valley and views of the Three Sisters have become particularly popular access points for activities and stops on tours. These are located below Am Bodach and The Chancellor. They are constructed on debris fans formed by flows of talus, the most recent of which occurred in the early-1990s. Their use was initially informal, but they were adopted and developed as car parks in order to make their use both safer and more practical from a traffic point of view. This work was to undertake a Quantitative Risk Analysis (QRA) of the risks to road users in moving vehicles through the Glen Coe and to those road users who choose to park at the two aforementioned car parks.

Fig. 1: Glen Coe, facing east towards the car parks, from Loch Achtriochtan.

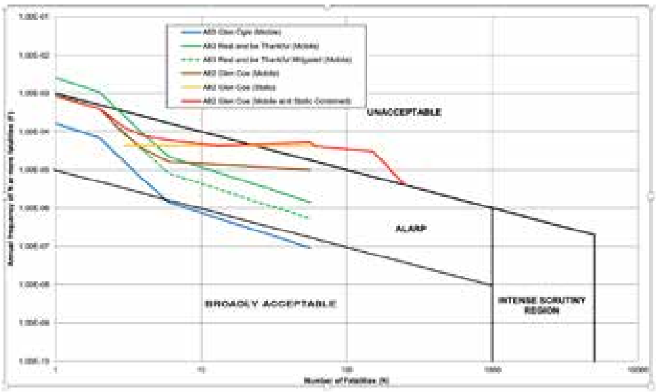

Fig. 2: F-N curves for the sites mentioned.

Methods: In order to calculate the quantitative risk for mobile elements at risk (EaR) the methodology developed and applied at A83 Rest and be Thankful and A85 Glen Ogle was used (Winter & Wong 2020). An entirely new method was developed for the static EaR, albeit following the same process. The main challenge was defining the EaR as neither data, nor an accepted metric existed. Accordingly, a new approach to collecting and analysing car park visit data was developed. This allowed the determination of the metric, Annual Average Daily Visits (AADV), which is analogous to Annual Average Daily Traffic (AADT), an important metric in traffic studies and in the QRA for mobile EaR.

Results: For mobile EaR, the risk falls in the ALARP zone and for values of N up to and including six, lies between the A83 and A85 (Figure 2). For the highest N value (56) the risk is higher than that at the other sites reflecting the greater number of buses and coaches that use the A82. For static EaR (and the cumulative risk), the risk for values of N between 3 and 13 plots within the ALARP zone, while for higher values of N (up to 250) it plots in the zone in which the risk is considered to be unacceptable.

Conclusions: The most prominent feature of the risk profile at the A82 Glen Coe is that the risk becomes less acceptable for higher numbers of fatalities (N). It seems clear that some form of landslide risk reduction is indicated for the car parks in Glen Coe and discussions between Transport Scotland and stakeholders have commenced.

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CHARACTERISTICS OF LANDSLIDES AFFECTING ROAD NETWORKS IN ETHIOPIA: EVIDENCE FROM 25 YEARS DOCUMENTATION, RESEARCH AND PRACTICE

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Landslides and related ground failures are among the major geohazards in the hilly and mountainous parts of Ethiopia. This paper presents on the characteristics of landslides that have been affecting road networks in Ethiopia with evidence from documentation, research and practice in the last 25 years (1997-2022). Though landslides of different types and sizes are common in Ethiopia, the data presented in this study is on slope failures that have affected road networks but with areal sizes greater than 5000m2. The study involved: (i) field inventory and characterization of a total of 158 landslide affected road sections, (ii) field investigations of the geological, geohydrological and geotechnical conditions of each of the sites which included surface mapping, sub-surface investigation (test-pits, trenches, resistivity geophysical methods), and in-situ testing (strength, permeability), (iii) monitoring groundwater levels in some of the sites, (iv) measurement of flood levels of rivers/streams where the landslide affected roads are close to streams/rivers, (v) laboratory investigations of the physical and geotechnical properties of soils and rocks from the different sites, (vi) assessments of the association of the landslide affected sites with gully erosion, construction (excavation or loading), and other factors that could influence slope stability, and (vii) assessments on the performances of mitigation measures implemented in each of the sites. Results of the study revealed that, though small slope failures are common in Ethiopia, the major types of landslides causing damages on road networks are debris/earth slides with some debris/earth flows. These landslides have occurred in areas underlain by different rock types: basement rocks (metavolcanic and metasediments), glacial tillites/post-glacial sediments, limestone with shale intercalations, shale with limestone intercalations, and volcanic rocks. The maximum depths of failures for the different sites varied between 2.5m to 13.5m. Groundwater levels within the slopes were found to fluctuate between 0 to 3.5m below ground surface. In 60% of the sites, stream/river incision was observed at downslope sides of the roads. The landslide-road interaction of the different sites could be categorized into three: (a) failure of the upslope side of the road, (b) failure of the downslope part of the road, and (c) failure of the whole road section (including upslope, road and downslope parts). The adopted mitigation measures in the different sites included one or combinations of: retaining structures (gabions, masonry, concrete), drainage and benches. Evaluation of the landslide affected road selections show that: (a) in 57% of the sites the mitigation measures implemented could not achieve the intended purposes, (b) in all the sites, the shear strength parameters, groundwater levels, and depths of failures were not properly determined, (c) no rigorous slope stability analysis was carried out which lead to faulty design of mitigation measures, and (d) the landscape-road interaction is poorly understood. With the planned expansion of road networks, the hilly/mountainous nature of the country, limited capacity (human and institutional) and rainfall variability (due to climate change), the effects of landslides on road and railway networks in Ethiopia is expected to increase unless due attention is given to such hazards. This calls for strong collaborative research and capacity building (at national and international levels) to address landslides and related geohazards in Ethiopia and in other Sub-Saharan African countries with similar challenges.

Keywords: Failure mechanisms, Landslide mitigation, Slope stability, Transport infrastructure.

INNOVATIVE APPROACH OF QUANTITATIVE RISK ANALYSIS FOR SLOW-MOVING LANDSLIDES: A STEP TOWARDS A NATIONAL ASSESSMENT

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Landslides are a serious worldwide hazard, especially in Italy where they are a serious threat to the population safety and structures causing damages and casualties every year. Social and economic impacts can be reduced by means of excellent urban planning and mitigation strategies which are undoubtedly facilitated by quantitative risk analysis (QRA). The purpose of this study was to conceive, test and verify the soundness of a methodological approach of QRA for slow-moving landslides in terms of expected damages to buildings and land-use replicable at national scale in order to provide a powerful tool for land planning and prioritization of economic funds for landslide risk reduction. The approach was tested in the Arno River basin (9100 km2, Central Italy) which is particularly affected by slow-moving landslides. The landslide risk analysis was defined following the equation: Risk = Hazard x Vulnerability (Intensity) x Exposure and it relies on the use of freely available open data at the Italian national scale to compute the different components of the risk equation adopting a 1km2 spatial resolution. Risk analysis was performed separately for each type of considered elements at risk (buildings and land use), and the results were aggregated expressing the total risk. The validation process was carried out analyzing freely available dataset and products of previous research, especially data concerning the expenses spent on landslide remediation or risk mitigation measures were collected in order to verify the soundness of our findings. Our results showed highest possible economic losses due to landslides in the selected case study reporting a total landslide risk of about 7 billion € and a mean value of 0.95 million €. Building components played a relevant weight in the definition of the total risk: specifically, building exposure is five times higher than of land use one, and this difference is accentuated by vulnerability, which is typically greater for buildings than for land use. However, the outcomes of the validation process showed a robust correlation between most of the testing dataset and risk values, highlighting the accuracy of our analysis. The proposed approach is an advance step towards quantitative risk analysis at national scale and it presents several novelties, mainly concerning the identification of the datasets and the development of new methodologies, such as the building vulnerability assessment, that could be applicable over such large areas.

CONSEQUENCE - FREQUENCY MATRIX AS A TOOL TO REDUCE THE LANDSLIDES RISK

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Purpose: Since F-N curves have been proposed, the use of Consequences-Frequency Matrices (CFM) has been extensively used in several domains. It is a common guide for many applications, including project management. They are diagrams with consequence and frequency classes on both axes. They permit classifying risks based on expert knowledge with limited quantitative data or more quantitative approach. But they are often misused and not well applied, because some simple rules are not well followed. Furthermore, they are often not used to visualize the evolution of risk with time or mitigation, or to represent uncertainty.

Methods: Here we propose first to provide the recommendations about the matrix construction as proposed by previous authors. In addition, the use of decision's trees is recommended to enter in the matrix as it is performed in fast assessment for epidemiology. The method to display paths of the risk with system evolution with time and risk reduction is proposed, adding the variability considering the different scenarios. Furthermore, the use of F-N curves is most of the time not relevant, since the hypothesis used are unclear, i.e., because it must indicate the support on which the acceptability and tolerability limits are based, because it can be used without reason depending based on the population involved or the geographical domain involved. Furthermore, a third dimension can be used to represent the uncertainty, the ease to reduce the risk or the uncertainty.

Results: Synthetic examples applied to landslides are proposed to illustrate the different aspects. In addition, it can include Bayesian approach to provide scenarios probability to belong to each box.

Conclusions: The use of such matrices is not new, but we think that it is needed to better use them to represent an explore risk situations and to also communicate risk level and scenarios.

HAZARD MAPS AS A BASIS FOR MULTI-SCALE AN TARGET-SPECIFIC RISK ANALYSES IN THE AUTONOMOUS PROVINCE OF BOLZANO - SOUTH TYROL

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Purpose: The Autonomous Province of Bolzano (APB) introduced hazard maps at the municipal level in 2007 in order to control urban development and building activities according to the principle of risk reduction. In this context, the hazard maps prove to be a very important instrument, not only for spatial planning prevention, but also for the planning of protection measures and civil protection activities.

Methods: In defining the hydrogeological hazard, the APB has followed the natural hazards assessment method developed in Switzerland by the Federal Office for the Environment, Forests and Landscape (BUWAL). This is based on the definition of hazard as a function of the intensity and probability of occurrence. In South Tyrol, hazard mapping framework consider only the mass movements, floods s.l. and avalanches. The key point of South Tyrol's hazard maps is that the plausibility of the final results, the delimitation of the hazard zones and the definition of the hazard levels are checked on the basis of surveys, documentations of past events and confrontations with local experts and stakeholders. In order to elaborate hazard maps with reasonable time, financial and human resources, not the whole municipal area is investigated, but only settlement, infrastructures and areas with potential urban development. Based on approved hazard maps, the public administration and other stakeholders thus have a very good basis for multi-scale and target-specific risk analyses. The intersection of hazard maps with different data exposure, collected in a specific database, via different geoprocessing routines, opens up a multitude of possibilities; exposure data examples are:

- Addresses with number of inhabitants and companies with number of employees;
- Number and type of buildings;
- Strategic civil protection facilities;
- Transport infrastructures (with characteristics such as average daily traffic volume);
- Network infrastructures (electricity, water, wastewater, telecommunications).

Results: From these databases, comprehensive possibilities for carrying out qualitative, semi-quantitative and quantitative risk analyses arise with regard to scale-dependent and target-oriented approaches:

- Realization of object protection measures through targeted compatibility analyses at project level;
- Risk analyses as an objective basis for the financing, project planning and implementation of protective measures, both at process level and for variant studies;
- Prioritization of protective measures and corresponding cost-benefit analyses as well as comprehensible planning with the limited financial resources available;
- Statistical analyses and development of regional risk zone maps as well as further development and expansion of the catalogue of protected goods as a fundamental data basis.

Conclusions: The PAB is a strategic player in natural risks management and therefore is responsible for defining and maintaining the methodological and informative basis for risk assessment. The PAB has established therefore a qualitatively high standard for hazard mapping that makes it possible to assess potential risks at different spatial scales and for different purposes; this quality level requires constant alignment with the state of the art.

The PAB also maintains a database describing most of the elements exposed on the territory; the expansion and more detailed characterization of this database will allow a progressive shift towards more quantitative risk analyses.

SESSION 2.4

MULTIPLATFORM AND MULTISENSOR APPLICATIONS FOR LANDSLIDES CHARACTERIZATION AND MONITORING (part I)

LANDSLIDE MONITORING BASED ON RFID REMOTE SENSING

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Purpose: Radio-Frequency Identification (RFID) shows great potential for earth-sciences applications [1], notably in landslide surface monitoring at high spatio-temporal resolution [2] with meteorological robustness. We propose to present the recent advancements of the technique of RFID landslide monitoring, which has proven its centimeter-scale accuracy over yearly-monitoring periods.

Methods: The RFID relative ranging method is based on Phase-of-Arrival measurements [3], with a fixed reader antenna placed on stable ground, and moving RFID tags placed on the landslide. A crucial step of the inversion is the phase unwrapping process, which has been thoroughly investigated and improved for the landslide monitoring application [4]. Furthermore, the possibility to measure the RFID tags position from Unmanned Aerial Vehicles is currently investigated, with a moving antenna using the Synthetic Aperture Radar technique.

Results: 2D relative localization was performed [5] and compared with optical reference measurements. The spatio-temporal accuracy of the method allowed for a thorough exploration of the landslides mechanisms during a 6-months period of activity. Data clustering was applied to the RFID data and groups of tags with coherent behavior were identified, allowing a fine description of the kinematic motion of the landslide blocks and various mass transfer mechanisms. Each identified block can be monitored individually. This opens the way for understanding the fine-grained activation processes at the local scale (tens of meters). The Synthetic Aperture Radar method yields promising results for 1D localization under vegetation and snow cover.

Conclusions: RFID landslide monitoring allows dense observation of ground surface movements at a centimeter scale and with sub-hourly time precision, and new results bring a finer understanding of the landslides inner mechanisms.

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6th WORLD LANDSLIDE FORUM
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INTEGRATION OF ROBOTIC TOTAL STATION AND DIGITAL IMAGE CORRELATION TO ASSESS THE THREE-DIMENSIONAL SURFACE KINEMATICS OF A LANDSLIDE

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Purpose: The assessment of the surface spatially-distributed three-dimensional (3D) deformation is crucial in landslide monitoring, as it represents the landslide kinematics. However, there is a lack of technologies that can provide this datum effectively and they are often limited by financial and/or logistic issues. We have developed a methodology to fuse displacement data obtained by robotic total station (RTS) and time-lapse camera, whose images we processed with digital image correlation (DIC).

Methods: Our technique adopts the 3D RTS measurements at specific points (i.e., corresponding to reflective prisms) to calibrate a transformation from the two-dimensional (2D) spatially-distributed DIC observations into 3D data. The algorithm involves a series of steps: i) DIC measurements are orthorectified on an available digital elevation model and represented in the local coordinate system of the time-lapse camera, obtaining the 2D displacement vectors that lie on the image plane (z and x components). ii) The RTS data are rototranslated into the camera coordinate system. iii) The ratio α between the z component of the RTS displacement vector and the module of the RTS displacement vector is calculated in the available measurement points. iv) The point values of α are spatially interpolated over the landslide active domain. v) The DIC displacement map of the z component is divided by α to obtain the spatially-distributed module of displacement (the third displacement component is simply derived using the Pythagoras Theorem). vi) The results are rototranslated from the camera coordinate system into the geographic coordinate system (Figure 1). The most critical element of the data fusion is the spatial interpolation of α across the landslide domain. Actually, the availability of a dense network of RTS measurement points, compared to the landslide extension, is not common in real monitoring. Therefore, α might suffer strong approximation in the presence of complex kinematics. Nevertheless, since α is a composition of non-independent displacement components, it is expected to vary smoothly and, therefore, it should be efficiently interpolated even with a limited number of measurement points. We conducted simulations with synthetic data to quantify the uncertainty contribution of α interpolation, which is generally <10%.

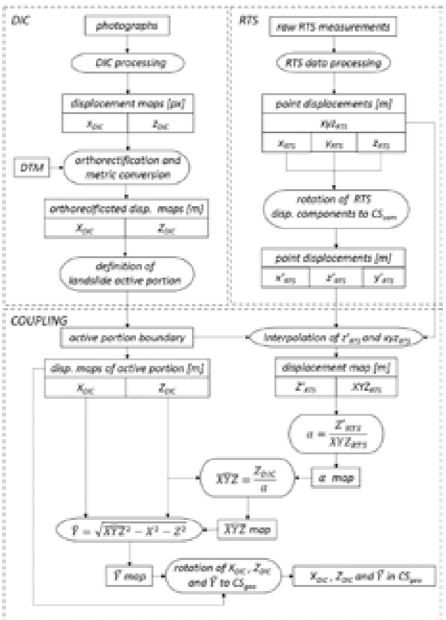

Fig. 1: Flow chart of the data fusion procedure.

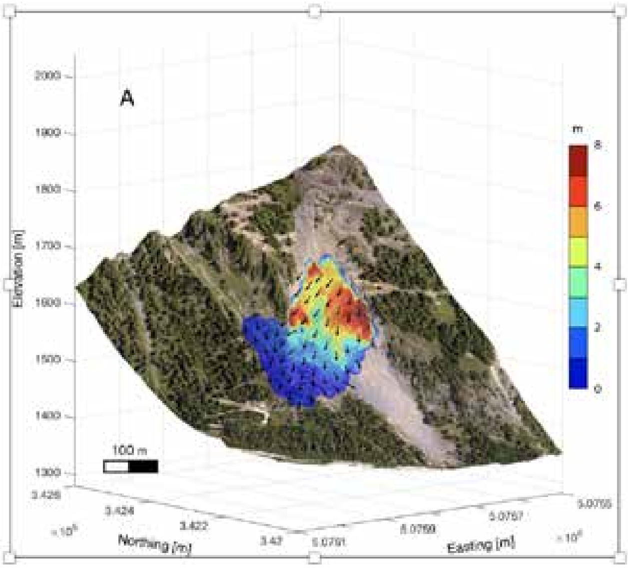

Fig. 2: Three-dimensional surface displacement of the Mont de La Saxe Rockslide between 16-17 April 2014.

Results: We successfully applied the RTS-DIC data fusion to the monitoring dataset of the Mont de La Saxe Rockslide, during a period of strong reactivation in April 2014, with displacement rates from ~0.1 m day-1 to >10 m day-1 (Figure 2). We proved the efficacy of the methodology comparing the obtained results with the independent measurements of a ground-based interferometric synthetic aperture radar, obtaining median deviation < 0.09 m.

Conclusions: The proposed monitoring solution has the advantage of involving low-cost and widely-used technologies, therefore it can be easily adopted in many other sites and monitoring contexts.

THE USE OF GROUND-BASED INSAR RADAR AND DRONE TO MONITOR AND WARN SUCCESSIVE SLIDES DURING THE RESPONSE AND RECOVERY PHASE, FOLLOWING THE CATASTROPHIC QUICK CLAY SLIDE IN ASK, GJERDRUM, NORWAY

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Purpose: The retrogressive quick clay slide, that occurred in the village of Ask, Gjerdrum municipality (Norway) in the early morning of 30th of December 2020, left a ca 1250 m long, steep and active scarp and a 20 m deep depleted zone. The landslide, with a volume of about 1,35 million m3 and a runout of about 2 km, caused the death of eleven people and destroyed many houses. About 1500 people were initially evacuated, making this event the most severe quick clay slide in the last 100 years in Norway. During the response and recovery phases, a temporary monitoring and warning system was established to warn rescue personnel, working below the scarp, about the possible occurrence of successive landslides. Such mass movements could put on risk or delate the rescue operations and the mitigation actions. We describe the experience acquired in the use of ground-based InSAR radar and drone for the detection of successive sliding events after a large quick clay slide.

Methods: The monitoring system was organized immediately after the main event. The first six days, the monitoring was done mainly with drone, thermal cameras and field observations and later also with the use of two ground-based InSAR radars. The area was monitored for over two years, from the 30th of December 2020 until 2023. All mass movements were mapped with the help of different sources (photos, video from drone and field observation and radar data).

Results: We present herein an overview of the landslides processes that occurred in the area from the 30th of December 2020 until the 31st of December 2021 (ca. 367 days), looking at their spatial and temporal distribution, magnitude, type of mechanisms and acceleration. Successive landslides were observed in 55 of these days, characterized as rotational slides with an initial volume ranging from 500 to 50000m3. The largest failures showed a retrogressive distribution and a flowing behaviour in the lower part, remobilising sediments already present in the runout zone. The failures occurred along the entire scarp, but most of them occurred in the eastern and northern part, due to the highest slope gradient and the presence of quick clay at the foot of the scarp. One failure was predicted with the use of drone and field observations, while about 20 others were predicted with the use of radar. The radar was able to detect areas of accelerating velocities, typically in a period of a few hours prior to failure, with the total amount of deformation commonly adding up to about 6-8 mm during the time of acceleration.

Conclusions: It is well known that successive slides may occur along the main scarp days and months after a quick clay slide, but this is, to our knowledge, the first-time that successive slides have been monitored and forecasted by using radar and drone. Ground-based InSAR data was a very valuable tool and probably the most effective and reliable method for monitoring deformations during search, rescue and mitigation works.

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VERIFICATION OF REMOTE SENSING METHODS FOR COMPLEX LANDSLIDE INNER DYNAMICS CHARACTERIZATION: A USE OF OPTICAL AND THERMAL UAV DATA

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Purpose: The aim of the study is to verify the utilization of optical and thermal Unmanned Aerial Vehicle (UAV) - borne data for characterization of the inner dynamics of a complex landslide. An active, small scale, but complex landslide near Březno village (Figure1), NW Czechia, was selected as testing site. Despite its active nature and real infrastructure impact, the studied landslide has not yet been systematically monitored. The Březno landslide is a rotational type of a slide, based in Cretaceous marlstones. The complexity of the landslide is formed by the second order movements (rockfalls, mudflows and toppling), which have developed at steep and high headscarp of the main landslide. These phenomena form instable accumulations with further impact on the main landslide movement.

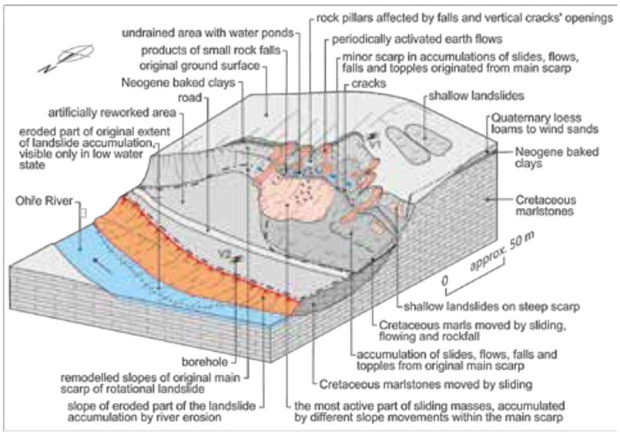

Fig. 1: Engineering geological model of the Březno landslide (Novotny, 2014).

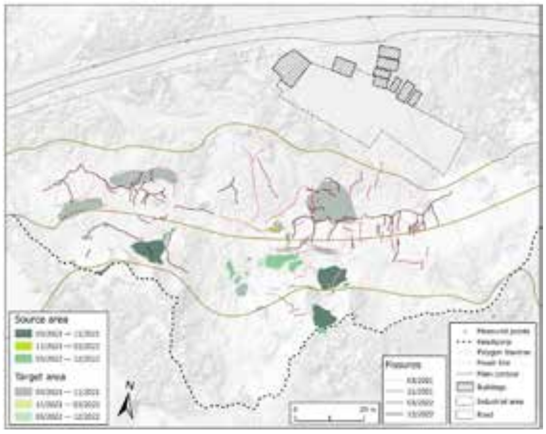

Fig. 2: Preliminary diagram of volume changes and fissures evolution between 03/2021 - 12/2022.

Methods: In contrast to the larger scale and slow-moving landslides, conventional methods such as radar interferometry or image correlation could not be used in this case. Instead, the time series of optical and thermal UAV-borne data has been used to study the inner dynamics of the landslide. These data were processed using the Structure from Motion (SfM) method (Lucieer et al., 2014) and thermometry respectively. UAV data acquisition, used for detecting inner landslide dynamics (i.e. volume and fissures evolution), was supported by precise geodetic measurements, which were used for the detection of actual main landslide movement.

Results: As a result of the surface models differencing, within three consecutive time periods, a diagram of inner landslide volume transfer has been developed (Figure 2). This diagram has been complemented by a fissures evolution diagram, based on simultaneous optical and thermal data deployment. A time correlation between fissures and subsequent mass movement has been confirmed. The movement of the main landslide has been estimated based on digital surface model differencing and also validated using geodetic measurements. These also provided 3D vectors, which show more complex movement trends of the main landslide.

Conclusions: Remote sensing methods helped to define the inner dynamics of the Březno landslide in detail and thus exhibit a big potential for updating the engineering geological model. Besides the SfM method, the deployment of compact UAV-based cameras (optical and thermal) indicated great potential for monitoring smaller scale, but complex landslides. This study shows how the use of rapidly developing remote sensing methods and monitored data interpretation, together with engineering geology methods, can effectively improve complex landslide mechanisms understanding and thus obtain better predictions of future developments with regard to hazard and risk planning.

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OBJECT-BASED LANDSLIDE DETECTION AND CHARACTERIZATION USING ML AND UAV PHOTOGRAMMETRY

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Modeling natural hazards in 3D space constitute a significant step for managing and planning our living environment. The creation of accurate 3D models is needed to document the impact of natural hazards such as landslides. Loss of life, natural resources or property transform landslide phenomenon to a natural disaster. Late years, the emerging geospatial technologies such as Unmanned Aerial Vehicle (UAV) or Unmanned Aerial Systems (UAS), support the acquisition of ultra-high detailed geospatial data in the 3D environment. The exploitation of 3D point-clouds has been proven tremendously efficient for analyzing data in the field of geoscience. Point cloud advantages of documenting in 3D space, data of hazardous sites at low cost and effective performance identifies them as leading primitives for site-specific 3D landslide modelling. Given the gaps between the computer vision capabilities and their applications in landslide assessment in site-specific scale, this work aims at developing a general framework of predefined workflows in an object-based programming environment for automated detection and characterization of landslide phenomena from ultra-high-resolution UAV-derived data. The framework is built up in four distinct research phases: (a) on-site data collection, (b) data preprocessing, (c) OBIA (segmentation and classification), and (d) evaluation. These phases result in various novel component-wise solutions, which particular focus on the optimization phase of OBIA for landslide assessment. An object-based classification approach of the photogrammetric point cloud products into homogeneous and spatially connected elements has been applied. The proposed framework has been developed based on Object-Based Image Analysis (OBIA) and fusion of multivariate data resulted from photogrammetric products. A quantifiable comparative study was conducted to analyze the influence of topographic information, scale segmentation and evaluate the object-based classification of landslide ontologies with three state-of-the-art Machine Learning classifiers, KNN, DT and RF with the inclusion of spectral, spatial, and contextual characteristics. Results highlight that RF presented higher predictive performance when the model was fitted and applied to a different study area. The proposed work illustrates the effectiveness of UAV platforms to acquire accurate photogrammetric datasets from complex surface topographies and provide an efficient and transferable object-based framework to characterize the failure site based on semantic classification of the landslide elements. The outcome can be useful for prioritizing efforts to moderate the adverse consequences of landslides and provide future mitigation strategies following landslide ontologies. Complementary to the developed workflow the accomplished real-world application, this work has shown the great potential of coupling UAV photogrammetry with object-based methods for assessing the landslide features in different hierarchical scales and provide a detailed automatic classification. Desirable data for further landslide analysis and OBIA include cohesion, friction angle, plasticity values, and groundwater data. There is still significant space to improve the reliability of object-based methods in the geotechnical domain. In the future, the applied methodology will be further extended and tested on diverse landslide mechanisms, also including engineering geological attributes.

COASTAL RETREAT CAUSED BY LANDSLIDES--MECHANISM AND MANAGEMENT

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Purpose: Coastal retreat is a big issue at Hoping Island Geopark, Taiwan. There were 8 landslides in the past two years and caused many problems for coastal management. The mechanism of landslides become a very important issues because of the landslides may cause many tourists dangerous hazards. How these landslides formed and the mechanism of these landslides is the main challenge to clarify and to adapt.

Methods: How these landslides formed and the mechanism of these landslides is the main challenge to clarify and to adapt. This study mainly focusses on the form and evolution of these 8 landslides at Hoping Island Geopark. By using UAV to get detailed 3D model and Data logger as well as seismological data to get weather climate and vibration information on the site.

Results: The study area is a coastal cliff at 40 m high and 200 m width. The 3D model at 2 mm resolution provides a very detailed fractures and joints information. The weather data provide the background information of rainfall data including total rainfall and rainfall intensity, duration. The results show that there are three main mechanisms to cause landslides.

Conclusions: The first mechanism is that the joint pattern to cause the sandstone very fragile which caused wedge form slide. The second character is that the weathering processes caused fragile debris into soil and fall down. The third character is that wave energy caused rock mass above sea cave to fall down. As a result, parallel retreat of cliff dominates the type of slope retreatment. However, another issue raised: what is the role of wave energy to the slope retreatment.

EO4ALPS-LANDSLIDES: ON-DEMAND TAILORED GEOINFORMATION SERVICES FOR LANDSLIDE MONITORING AND HAZARD ASSESSMENT

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Purpose: The “Geo-information Services for Landslides in the Alps (eo4alps-landslides)” application has the objective of exploiting the potential of new satellite data coupled to advanced modelling for gravitational hazards assessment in the Alpine region. “eo4alps-landslides” produces harmonised and advanced landslide inventories and susceptibility/hazard maps for the Alps based on advanced InSAR and optical ground motion services and landslide-specific models embedded in the Geohazards Exploitation Platform (GEP). These EO-based services and products can be complemented by local datasets and terrain data uploaded by users.

Methods: The services and products that can be generated on the application includes 1) automatic landslide detection services and maps using satellite optical and InSAR (SNAPPING, GDM-OPT-SLIDE), 2) harmonised and advanced landslide catalogues resulting from the satellite based detection and local inventories, 3) susceptibility/hazard maps consisting of possible landslide source areas and landslide runout modelling (FLOW-R). Landslide-tailored SqueeSAR datasets are accessible for 3 large regions in Swiss, France and Italy; the products have been generated with very-high resolution DSMs and specific processing has been setup for increasing the number of PS/DS points on landslides areas. Post-processing services for the analysis and exploitation of large ground motion datasets, such as large stacks of interferograms, PSInSAR time series, optical derived time series, are available. The TimeSAT service allows to classify ground motion displacement trends in specific behavior, detect changes in the time series (acceleration, deceleration, periodicity) and identify spatial clusters of homogeneous deformation; the service can be used in supervised and unsupervised mode, and is based on advanced machine learning models.

Results: Specific examples of products generated for either slow- and fast landslide monitoring, landslide inventory mapping, and landslide hazard assessment will be presented.

Conclusions: The eo4alps-landslides services can be used either for science and operational risk management purposes.

PHOTOMONITORING OF LANDSLIDES: A NATIONAL SCALE PROJECT

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Purpose: Photomonitoring is an innovative and experimental analysis technique that benefits and exploits the huge number of digital images and the wide diffusion of photographic sensors and acquisition platforms in the last decade. Through image analysis techniques, it is possible to identify, using differential comparison, the position and extent of the changes that occurred between a pair (or sets) of images acquired at different times (so-called Change Detection) or measuring with optical-numerical "pattern tracking" techniques, displacements or 2D deformations fields in orthogonal the plane to the line of sight of the camera (so-called Digital Image Correlation).

Methods: In this research, the photo monitoring solution has been applied to the systematic control of landslides in Italy, where a dedicated research infrastructure will be implemented in the frame of the Geosciences-IR project. Different sites and monitoring approaches have been selected to test the suitability and potential of these techniques, maximizing the managed landslide mechanism, and approaching the monitoring through periodic or continuous acquisitions based on aerial and ground-based platforms. Cameras with resolutions from a few mega to giga-pixels have been included in testing program, including digital photos acquired by mobile devices. Collected images are processed within an IaaS-HPC equipped with software suitable for image co-registration and alignment, automatic Change Detection and Digital Image Correlation data processing to allow the systematic monitoring of landslides.

Results: Results achieved from a pilot case study in the Poggio Baldi Landslide natural Laboratory (site of the WLF6 field trip) highlighted the potential of detection of small rockfalls through automatic selection of digital images acquired over time and subsequent change detection analysis. The first application of thermal images acquired by InfraRed thermography was also carried out in the laboratory under analogue testing reconstructing rainfall-triggered landslides in earth slopes.

Conclusions: Preliminary results proved the technique's potential, confirming the validity of photomonitoring as a viable solution for increasing the number of monitored landslides worldwide, opening new perspectives for the inventory of landslide effects and, consequently, in landslide hazard assessment.

SESSION 3.4

PHYSICAL AND NUMERICAL MODELLING OF LANDSLIDE-STRUCTURE-INTERACTION (LSI) (part I)

INTEGRATED 3D GEOLOGICAL AND FEM MODELING OF SLOW ROCK SLOPE DEFORMATIONS AFFECTING HYDROPOWER STRUCTURES

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Purpose: Slow rock-slope deformations are widespread in alpine settings and pose significant threats to critical infrastructures, due to continuing slow movements and potential collapse. A reliable analysis of the interactions between slope deformations and man-made structures requires realistic models. These must provide an adequate account of the 3D complexity of both landslides and infrastructures, often hampered by over-simplification of geological aspects in engineering practice. Here we propose an integrated workflow for the 3D modeling of a complex system of deep-seated landslides affecting a slope in Valmalenco (Italian Central Alps), made of a complex sequence of metamorphic rocks including metapelite, serpentinite, gabbro and gneiss with a regional foliation deformed in two folding stages. The slope hosts a hydroelectric power plant and related structures, affected by deformations that were observed since the 1970s. Although these deformations were related to gravitational phenomena, these were never characterized in detail.

Methods: We performed an accurate 3D geomodelling to provide sound constraints on the geometry, lithology, and mechanisms of the active landslides. We integrated field geological and geomorphological data, site investigations (field surveys, full-core borehole drilling, seismic surveys) and deformation monitoring (EDM, GNSS, structural monitoring, GB-InSAR). We reconstructed longitudinal and transversal cross-sections in MOVETM and performed implicit surface interpolation in SKUA-GOCADTM, eventually obtaining solid objects corresponding to tectono-stratigraphic units that are dissected by landslides. We characterized these volumes in terms of rock mass properties, interpolated from boreholes and surface surveys. Based on the 3D geomodel, we set up a continuum-based 3DFEM elasto-plastic model in MIDAS GTSNXTM, discretized into a 3D mesh of 150000 hybrid finite elements with variable size in the range 20-200 m. We considered rock masses as Mohr-Coulomb materials with tensile cut-off and post-peak dilatancy, and included landslide shear zones explicitly. We ran the model with a Shear Strength Reduction (SSR) technique, and calibrated model parameters using a quantitative back-analysis approach. This optimizes the fit between normalized GB-InSAR measured displacements and computed displacements, projected in the radar LOS.

Results: Our 3D geomodel shows a complex folded structure, providing constraints to the spatial distribution of weaker anisotropic rocks, and thus to the geometry, kinematics and shear zone properties of active landslides. The slope is affected by a deep-seated gravitational slope deformation and by a system of nested large landslides, including a toe failure and two suspended rockslides, that affect some of the hydropower structures. The 3DFEM model, validated against field evidence and effects on man-made structures, provided the starting point for a forward modeling of the slope response to different groundwater perturbation scenarios. These allowed assessing the critical conditions corresponding to different instability scenarios with different possible impacts on the hydropower structures.

Conclusions: Our results show that an explicit account for 3D geometrical and geological complexities is key to a realistic modeling of large slope failure mechanisms, their impacts on critical infrastructures and the evaluation of related risks.

EQUALIZATION METHOD OF SLATE DISCONTINUITY IN DISCRETE ELEMENT NUMERICAL SIMULATION

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Purpose: Near the confluence of Tiangul Creek and Lanyang Creek in Yilan, Taiwan, the rock stratum is dominated by slate. In this area, the slaty cleavage structure is densely developed, all sides of the creek have a similar dip angle and dip direction. However, the slope stability on both sides of the stream has shown different changes in the past two decades. The failure of rock slopes is highly affected by discontinuities. The first objective of this study is to develop a set of methods to determine representative numerical simulation parameters based on the results of in situ investigations and use historical collapse disasters as verification. Secondly, is to evaluate the impact of river erosion and aggradation on slope stability.

Methods: The methods used in this study include using the in-situ investigation to obtain discontinuity data such as: the persistence, spacing, dip, dip direction, etc. The results of the in-situ investigation would be combined with the numerical simulation using 3DEC software to carry out the result that can be analyzed. A digital terrain model (DTM) from LiDAR is used to establish the real terrain model in 3DEC. In the numerical model, slopes with different aspects are selected to establish numerical analysis models. The historical collapse disasters are collected from Central Geological Survey over years as verification of numerical simulation results. Through statistical analysis of variance (ANOVA), a regression formula was obtained. The parameters obtained from the formula were used as input values for the slope stability analysis of the case study.

Results: Figure 1. shows the process of numerical simulation model. First, the four slopes of different aspects are selected and extracted form DTM. Second, the selected slopes are transformed to cloud points and meshed. Finally, the model with real terrain can be imported to 3DEC to analyzed the slope stability.

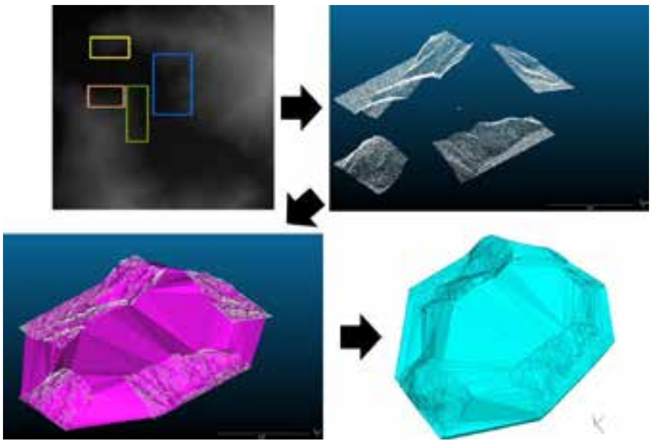

Fig. 1. The numerical simulation model establishment process.

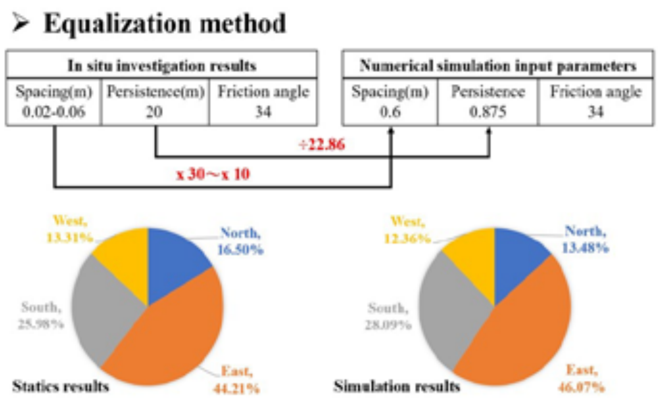

Fig. 2. The comparison between statics results and simulation result.

Figure 2 shows the simulation results and the statics results over years. When the parameters of numerical simulation such as spacing equal to 0.6 m, persistence equal to 0.875, and friction angle equal to 34, there shows a similar result to historical disasters over years. Accordingly, the relationship between investigation results and numerical simulation input parameters have been established. And the parameters from the numerical simulation can be considered as representative parameters which equalize the slope stability of the area.

Conclusions: 1) In this study, an experimental design method combined with numerical simulation is used to establish a numerical simulation parameter estimation method that can represent this area, and its feasibility is verified by in situ collapse disaster records. 2) In this study, the regression formula was obtained by ANOVA. The parameters obtained from the regression evaluation are used as the input parameters for the slope stability analysis of the case, and the simulation results are consistent with the actual situation, which verifies the correctness of the method proposed in this study, and can provide relevant case references.

EFFECT OF CYCLIC FLUCTUATIONS IN RESERVOIR WATER LEVEL ON THE STABILITY OF RIM SLOPE

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Purpose: Several reservoir-induced landslides have been witnessed due to water level fluctuations over past decades across the globe. Landslides occurred in Three Gorges Dam Reservoir (China), Bratsk Reservoir (Siberia), Xiangjiaba Reservoir (China), Vajont Reservoir (Italy), and San Luis Dam (United States) are few illustrations caused due to the water level fluctuations in reservoir water level. Ample literature is available on the effect of water level fluctuations on the stability of rim slopes from geomorphological, geomatics and geotechnical aspects. However, limited studies are available on physical modeling and hence the study becomes necessary.

Methods: An attempt has been made to study the effect of cyclic fluctuation in reservoir water level on the stability of rim slope through physical modeling. The study has been performed on an indigenously developed small-scale physical slope model test apparatus. For the study, the soil samples used to prepare the model rim slope of 25 cm was collected from an actual reservoir rim slope situated between Tehri and Koteshwar Dam (India). The test was conducted on a 45° modelled soil slope with drawdown and impounding rate of 2.67 cm per hour (0.64 m per day) and a hydro-fluctuation belt of 16 cm. The modelled slope was subjected to 30 cycles of water level fluctuations. Total head values through piezometers at various nodes and deformed slope profiles were recorded after every drawdown.

Results: The total head readings just after the drawdown was higher compared to that at the steady-state condition indicating lag in the response of pore water pressure within the slope mass with respect to water level fluctuation. With time, the excess pore pressure releases and total head values tend to decrease to the values as was observed at the steady-state condition. The total head values observed just after the drawdown remained higher for all the 30 cycles of water level fluctuations. A shallow toe failure was observed during the 1st drawdown causing significant deformation of slope profile and spread at toe. A new term spread index was defined as the percent spread at toe with the height of the slope at a given cycle and was assessed for all the 30 cycles. After the initial failure, rate of spread index remained constant as 0.95% per cycle; beyond 15th cycle, the rate of spread index reduced to 0.12% per cycle and remained nearly constant for the entirety of the test. Evolution of volume for the slope mass was evaluated and the slope volume expanded till the 15th cycle beyond which it remained nearly constant till the end of the test. Potential against sand boiling condition was examined at different interval of cycles. It was observed that after the 3rd cycle drawdown, the factor of safety against sand boiling condition in the lower slope face region reduced to unity and is critical.

Conclusions: It is concluded that the repeated cyclic fluctuations even at a slow rate affect the stability of slope and a debris slump kind of failure may be observed.

SEMI-ANALYTICAL FRAMEWORK TO SIMULATE TRIGGERING AND RUNOUT OF HYDRAULICALLY INDUCED FLOWSLIDES

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Purpose: Flowslides are a highly damaging class of landslides triggered by liquefaction. At variance with seismic forcing, during which flowslides are promoted by shaking and undrained loading, the emergence of static liquefaction during rainfall infiltration and rising water table is relatively less understood. In this contribution, a simplified modeling framework able to link sand deformation, excess pore water pressure development, and flowslide dynamics is discussed, with the purpose to shed light on the coupled processes that give rise to hydraulically induced static liquefaction.

Methods: A spatial condensation procedure is used to resolve the dynamics of excess pore pressure growth in an inelastically deforming saturated zone whose thickness grows in response to rainfall-driven water table rise. In conjunction with this process, the model also resolves the inertial dynamics of the mass overlaying the saturated zone. This condensation procedure generates a coupled system of ordinary differential equations allowing the examination of the temporal sequence of pre-failure deformation, instability, and post-liquefaction runout with low computational cost. Most notably, the framework can be used in conjunction with any constitutive relation for the soil within the saturated zone. In this work, the analyses are conducted with a critical state model with non-associated plastic flow by constraining its parameters to replicate the mechanical behavior of a loose sand.

Results: The simulations indicate that the temporal dynamics of a flowslide is regulated by the ration between the rate of loading with to characteristic timescales of the system: the rate of excess pore pressure dissipation and the rate of inertial response. Depending on the ratio between such timescales different regimes of motion can be found, spanning from undrained, to partially drained, to quasi-drained regimes. Most importantly, the model shows that a spontaneous transitions from drained to undrained behavior is possible depending on how the plastic response of the sand regulates the abovementioned timescales during the loading process.

Conclusions: The results show that the spontaneous emergence of static liquefaction during hydrologic forcing requires specific combinations of material properties, loading rate, and timescale of pore water pressure dissipation. As a result, its occurrence cannot be predicted unless the nonlinear dynamics of the problem regulated by the inelasticity of the material is taken into account. This in turn requires analyses conducted by accounting for the interaction among constitutive behavior, hydro-mechanical boundary conditions, and temporal history of loading.

THE EFFECTS OF THE INHERENT DISTRIBUTION OF DISCONTINUITIES AND STRESS-INDUCED ANISOTROPY ON PORE WATER PRESSURE DISTRIBUTION OF ROCK SLOPES

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Purpose: Rock slopes with a significant number of fractures present a challenging task for characterizing their hydraulic properties, as complex fracture networks are the primary pathways for fluid flow. The geometry of the discontinuities, including their orientation and aperture, significantly affects the permeability tensor, and understanding these properties' impact is crucial. Although numerous review papers have demonstrated the use of discrete fracture networks for modeling rock slopes, their high computational demands require a significant amount of detailed input data. To address this challenge, the study employs a continuum approach that establishes a statistical equivalence between constitutive parameters from an equivalent continuum and those of a discrete fracture network. This study focuses on examining how the constitutive parameters, including the orientation and aperture of discontinuities, impact the pore water pressure distribution in rock slopes.

Methods: The study investigates how pore pressure distribution affects rock slopes by examining the inherent distribution of discontinuities and stress-induced aperture change. First, the study employs a continuum approach to calculate an equivalent permeability tensor, which is then incorporated into a simple geometry rock slope model. Next, the steady-state pore water pressure is established by analyzing fluid flow through FLAC 3D. Finally, the study utilizes the shear strength reduction technique to calculate the safety factor results.

Results: When examining the impact of uniform and non-uniform stress fields on pore water pressure, the maximum relative variation observed is 21%. However, this variation does not significantly affect rock slopes' safety factor or shear strain increment zone. Next, the study analyzed the influence of different anisotropic levels of discontinuities under a uniform stress field. The results showed that when the number of strike joints is significantly greater than dip joints, the maximum relative variation in pore water pressure is 51%, decreasing the safety factor. However, under a non-uniform stress field, the safety factor relatively increases in the same situation.

Conclusions: While the stress field alone may not significantly impact the rock slope safety factor, considering the anisotropic distribution of discontinuities under uniform and non-uniform stress fields reveals a significant effect on stability. Thus, it is crucial to consider the hydraulic characteristics influenced by discontinuity properties in rock slope stability analysis.

PORE WATER PRESSURE RESPONSES WITHIN THE LANDSLIDES WIRG COMPLEX STRUCTURES TO RESERVOIR WATER LEVEL FLUCTUATIONS AND THEIR INFLUENCES ON LANDSLIDE REACTIVATION PATTERNS — CONSTRAINTS FROM PHYSICAL MODEL TESTS

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Purpose: Pore water pressure (PWP) has long been recognized to be one of the major causes responsible for the reactivations of old landslides in reservoir areas during water level fluctuations. However, it remains unclear how PWP varies within the landslides with complex structures during water level fluctuations. In order to investigate variations in PWP responses to reservoir water level fluctuations within the landslides with complex structures and their effects on landslide reactivation mechanisms, a series of physical model tests were conducted.

Methods: The landslide models were composed of three slip zones and three layers of soils ranging from clayey silt to gravelly sand to feature the landslides with complex structures, particularly those with multiple slip zones and multiple layers whose permeabilities are sharply distinct. Of the models, the sequences of the three layers were different, and the three slip zones were the same. The PWPs within the models and displacements on and within the models were monitored using mini-sized piezometers sensors and serial fiber grating strain sensors that were specially made, respectively. Reservoir water level fluctuations were controlled through water faucets linked to inlet and outlet pipes.

Results: The results revealed that PWP responses to water level fluctuations within all landslide models were layer-specific, showing that both types and magnitudes of PWPs within each layer were different during water level rising and drawdown periods. All landslide models showed a layered-slipping displacement pattern with fluctuant or intermittent dynamics, but the slipping layer(s) varied among the models. During the water level rising period, pronounced uplift (water) pressure was observed within the most permeable layer when it was sandwiched by or under the less permeable layers, and prominent inward seepage force was observed within the least permeable layer. This was accompanied by displacements of the layer(s) above the most permeable layer and few or no displacements of the least permeable layer. During the water level drawdown period, the most rapid dissipations of PWPs and prominent outward seepage force occurred within the layers that were the most and the least permeable layers, respectively. This was along with a decrease in displacements of the layers above the most permeable layer, and an increase in displacements of the least permeable layer when it was on top of the models. Either uplift pressure or seepage force increased with the water level rising or drawdown rates, together with variations in displacement magnitudes of the models.

Conclusions: PWP responses to reservoir water level fluctuations within the landslides composed of layers with sharp distinctions in permeability were layer-specific. Reactivation patterns of the landslides were also layer-specific. Types of PWPs and their dissipation rates were significantly different within the layers that were the most permeable and the least permeable during water level fluctuations, thus leading to variable reactivation mechanisms among the landslides with the layers in different sequences. These findings were helpful for better understanding the reactivation mechanisms of old large landslides with complex structures in reservoir areas.

REDUCED ORDER MODELLING OF DEBRIS RESISTING FLEXIBLE BARRIERS FOR DIGITAL TWIN DEVELOPMENT

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Purpose: Flexible barriers have emerged as robust, economical and environmentally friendly solutions for protecting infrastructure from flow-like landslides and debris flows in recent decades. With large number of barriers spread along mountainous terrain, digital twin technology provides a unique opportunity for operational as well as life-cycle assessment of these assets. Three-dimensional finite element (FE) models of debris resisting flexible barrier systems with explicitly modelled components are computationally intractable for use as digital twins. Reduced order models of flexible barriers can act as a proxy of high-fidelity finite element models by capturing key physical responses at a fraction of computation cost. Parameterized reduced order models can then be deployed in operational digital twin system for data-driven real-time monitoring, impact detection and maintenance decision making.

Methods: Physics-based reduced order models of flexible barriers are derived from component-based model order reduction of high-fidelity finite element model. The reduced order models are parameterized to capture a wide range of states of the flexible barrier and compared with the full-order model for verification. Static-condensation with reduced-basis-element is used to formulate the flexible barrier system into substructure components. This component-based formulation allows parameterization of a complex nonlinear dynamical system into multiple simple components using a reduced-basis method on each component. The reduced order model is then verified using flexible barrier deformation modes obtained on a full-order finite element model.

Results: Static-condensation with reduced-basis-element method provides a flexible and scalable approach to develop component level reduced order models of complex nonlinear dynamical systems. The reduced order model is compared with a validated full-order model to capture different states of the flexible barrier. The experimental results of peak deformation and curvature of a rectangular panel of flexible barrier under its self-weight as well as boulder impact while supported on four edges with cables is used in validating the high-fidelity finite element model and the component based reduced-order model. Furthermore, the component-based reduced order model reasonably captures the eigenmodes of the flexible barrier computed using the validated finite element model.

Conclusions: Reduced order models formulated using component level reduced basis method for complex nonlinear dynamical systems like flexible barriers can reasonably capture the physical response under different states. These reduced order models also provide a huge computational savings with flexible parameterization compared to full-order models. Component-level reduced order models can serve as proxy to full-order models when deployed in digital twins.

OVERFLOW AND LANDING DYNAMICS OF DEBRIS FLOW INTERACTING WITH A RIGID BARRIER: TWO-PHASE MPM MODELLING

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Purpose: The existence of excess pore-fluid pressure in debris flow contributes to disastrously large flow mobility which necessitates the erection of debris flow impeding barriers to avoid fatalities and mitigate damage to infrastructures. Despite the vital role of pore-fluid pressure, modelling its evolution during debris flow interaction with barriers remains challenging. The existing numerical modelling methods typically idealise the two-phase debris flow as a single-phase frictional or viscous material, regardless of the evolution of pore fluid pressure. Thus, the existing design of debris flow barriers may not be conservative and warrants further investigation.

Methods: In this study, a fully coupled, two-layer, two-phase material point method (MPM) is implemented to investigate the overflow, and landing dynamics of debris flow against a single rigid barrier. A constitutive model that can capture the shear rate-dependent friction angle and dilatancy is utilized for solid phase, where the mixed inertial number Im governs the shear rate-dependency. An additional compression cut-off considers the maximum mean effective stress under specific shear rate and solid fraction. The fluid phase is modelled as a Newtonian fluid, in which shear stress is linearly proportional to shear rate. Interphase forces include buoyancy force due to pore-fluid pressure gradient and drag force due to relative motion between fluid and solid phases. Debris flow with an initial volume of 500 m3 is modelled to interact with the single barriers in plane-strain simulations. Flow Froude numbers are ranged from 2 to 6 to model flow conditions from gentle to steep terrains and barrier heights are varied from 1.5 to 2.5 times of peak flow depths.

Results: The effects of flow Froude number and barrier height on overflow and landing dynamics will be reported. The fluidisation ratio, which is defined as the ratio of pore-fluid pressure and total stress, during landing will be shown to emphasize the importance of two-phase simulation. Shear rate and mixed inertial number (Im) will be presented to highlight the necessity of considering shear rate-dependent characteristic in modelling flow-barrier interaction.

Conclusions: New insights and findings drawn from the study can help engineers to design safe and economical debris flow barriers.

SESSION 6.7

4D HIGH-RESOLUTION TOPOGRAPHIC SURVEYS TO SUPPORT THE ANALYSIS OF SLOPE INSTABILITY PROCESSES IN HIGH-STEEP SLOPE AGRICULTURAL AND FORESTED LANDSCAPES

USING PRE- AND POST-EVENT LIDAR DATASETS TO ASSESS ECO-HYDROLOGIC LANDSLIDE MODELING

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Purpose: One of the main challenges in modeling geomorphic processes like rainfall-induced landsliding is validating results with ground truth data. Puerto Rico is an ideal study site to assess the performance of landslide modeling efforts, given that tens of thousands of landslides triggered by Hurricane Maria in 2017 have been catalogued and characterized with the use of high-resolution aerial imagery and pre- and post-event LiDAR surveys. In addition, specific regions of the island have been the study site for advanced hydrologic/landslide modeling in the past (e.g., Arnone et al., 2023). The abundance of data in Puerto Rico presents an ideal opportunity to test advanced landslide modeling techniques.

Methods: Using the pre-event LiDAR-derived topography for a 24 km2 target sub-basin (Rio Saliente) in central Puerto Rico (Figure 1), we will present the result of a distributed basin simulator with the tRIBS-VEGGIE-Landslide eco-hydrological model. This basin is underlain by Cretaceous intrusive and volcaniclastic bedrock units that are part of the arc-basement complex on the island. Previous work (Bayouth-Garcia and Hughes, 2023) showed that the 516 Hurricane Maria landslides in the basin are more concentrated in the sandy soils that develop in the intrusive rock bedrock units. The landslides in the basin range several orders of magnitude in size, but average 140 m2 in area and 1 m in depth.

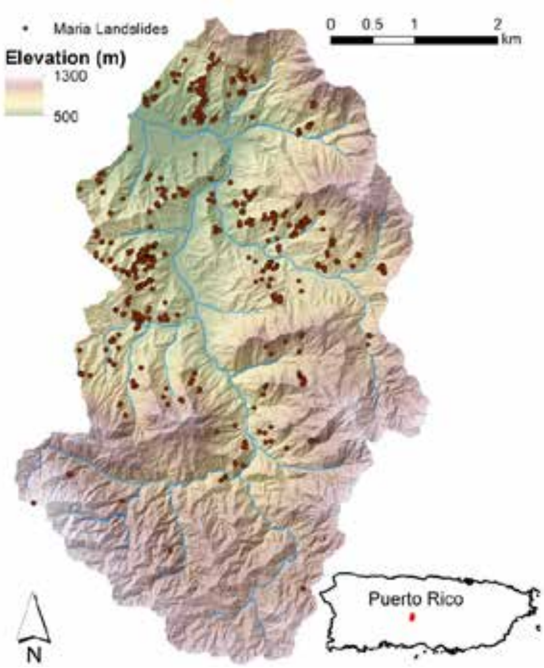

Fig. 1: Rio saliente study basin in central Puerto Rico, red polygon in inset map shows its location

The chosen model implements a stability component into a spatially distributed physically-based hydrological model coupled to a model of plant physiology and spatial dynamics. The topography is considered as an irregular spatial mesh based on a Triangulated Irregular Network (TIN), which allows for the use of variable computational elements to describe the basin topography. This peculiarity allows the analysis of the detail of the available lidar data at 1 m resolution. The stability model accounts for the soil-water characteristic curve and the saturated shear strength parameters (cohesion and friction angle) to assess the factor of safety (FS) in space and time.

Results and Conclusions: The study is in its initial stages. The landslide model is calibrated using hydrologic data (streamflow, soil moisture) and the topographic digital elevation model before Hurricane Maria, as well as parameters from previous simulations in other parts of the island (Arnone et al., 2023). The calibrated model is then forced with Hurricane Maria precipitation in order to compare modeled vs. observed landslide sites. The high-resolution digital elevation model presents computational challenges that will be detailed in our presentation.

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POINT CLOUDS FOR TERRAIN MONITORING IN VEGETATED AREAS

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Purpose: In the last decades, landslide monitoring has benefited from the development of remote sensing techniques, which allow extensive, high-detailed and repeated surveys. For such application, modeling the bare terrain surface is of fundamental importance, implying the adoption of appropriate instruments able to "see" beneath the vegetation that often covers the area of interest. To this end, one can resort to active systems such as LiDAR (Light Detection and Ranging), whose signals can penetrate through gaps in the forest canopy, measuring points on the ground. Recently, LiDAR sensors are increasingly used as UAV (Unmanned Aerial Vehicle) payload, favoring their diffusion to a wider spectrum of applications. This contribution aims therefore to analyze advantages and limitations of ULS (UAV-borne Laser Scanning), highlighting complexity of terrain monitoring in vegetated areas.

Methods: This work starts from a literature review, focused on the papers that evaluate the use of ULS in the environmental monitoring domain. The majority of the articles found are related to forest inventory, where point clouds provided by ULS are mainly employed for crown structure metrics assessment. Being the terrain an essential information for the vertical structure modeling of forests, attention is also given to point cloud filtering, fundamental to obtain accurate DTMs (Digital Terrain Models). Furthermore, to give insights on ULS performance in the presence of low vegetation, in this contribution we evaluate the case study of a river bank, the survey of which is aimed at modeling the ground geometry for subsequent stability assessment. Data acquisition was performed by globaRT srl with a DJI Matrice 300 RTK equipped with the Zenmuse L1 laser scanner. The ULS point cloud was filtered with Terrascan software to extract ground points, used for DTM interpolation.

Results: From the literature analysis, it clearly emerges that ULS represents a powerful platform to study canopy features. However, the canopy penetration ability is strongly affected by scanner settings and flight properties, including pulse repetition rate, number of returns recorded, scan angle, leaf-on/leaf-off conditions. Moreover, several papers highlight how the presence of dense vegetation negatively influences the accuracy of the DTM, showing that occlusions at the bottom of the canopy cannot be easily overcome with ULS. These limitations are further confirmed by the analyzed case study. As shown in Figure 1, the ground is accurately mapped below the trees (Figure 1a), whereas brushes and dense riparian vegetation prevents the laser pulse from reaching the bare ground (Figure 1b). As a consequence, the DTM is affected by a mean error of di +0.179 m (+/- 0.157 m), estimated on 202 GNSS-measured points.

Conclusions: This work is part of an ongoing research that aims at defining best practices for terrain monitoring in vegetated areas. These preliminary results show the limits of ULS in the presence of low vegetation. In this context, data fusion and the integration of terrestrial topographic techniques appear essential to obtain a complete and accurate DTM.

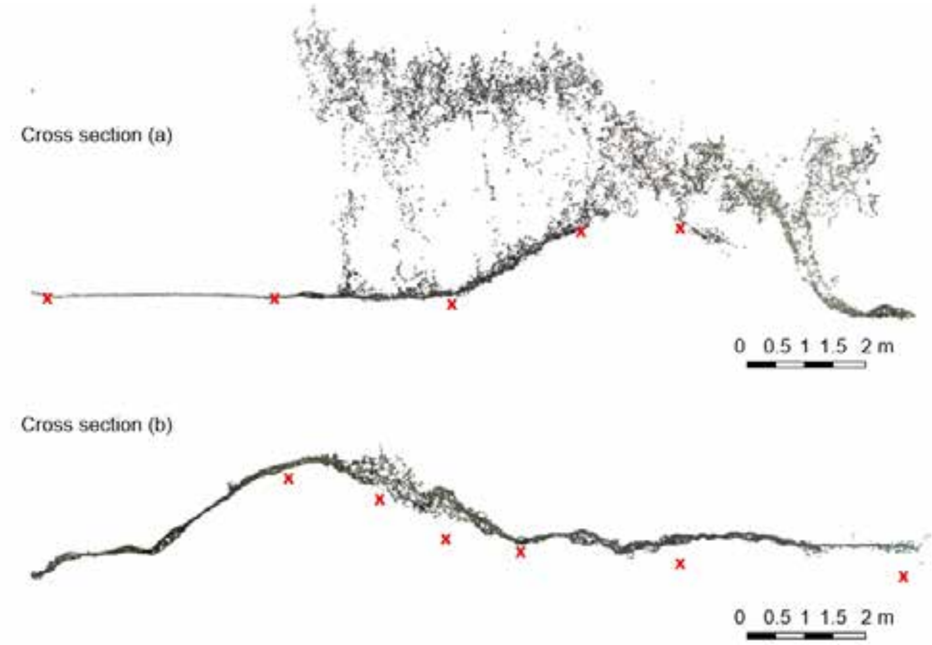

Fig. 1: Cross sections of the river bank surveyed with ULS. Red crosses represent the GNSS-measured points.

COUPLING LIDAR AND SFM HIGH-RESOLUTION DEMS FOR LANDSLIDE MONITORING IN STEEP HILLY AREAS WITH MIXED LAND-USE

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Purpose: The recent advances in the acquisition of aerial images using Remotely Piloted Aircraft Systems (RPAS) offer an efficient and low-cost solution for the assessment of permanent changes of the topography in highly dynamic areas (landscapes with the dominance of landslides, gullies, and rill erosion, river channel migration). The quality of images allows us to create accurate Digital Elevation Models (DEM's) in every critical moment linked with heavy rainfalls, which may trigger the reactivation of old landslides. Despite many advantages of DEM's obtained through Structure from Motion (SfM) method (resources, availability, high resolution - spatial and temporal), they can be achieved for small surfaces, usually under 100-200 ha. Therefore, they are realized in areas with a significant representation of the processes' dynamics and the threatened sites' value.

Methods: The present study focuses on the area of Poiana Mănăstirii – Între Şanţuri thraco-getic fortress (2550-2050 yr BP), located in the central part of Moldavian Plateau, NE Romania. Covering a surface of 12 ha, the fortress is partially surrounded by a 2-3 m high wall, with a 10 m wide base and a 1 m deep and 4-6 m wide trench. In its southern part, the landslides destroyed these remnants, and due to the deforestation of the slope in the last 30 years these processes recorded almost yearly reactivations. A DJI Phantom 4 Pro UAV was flown over the study area in October 2019 and acquired images with 80% side and forward overlap at 20 MP resolution. Metashape software was used to obtain the point cloud, and a Ground Control Point network (determined with a Trimble GeoExplorer 6000 GPS) was used for georeference. In order to detect and map geomorphic changes, LiDAR point clouds (2012) were used as reference dataset (with a spatial resolution of 0.25m and a vertical accuracy of 0.13 m). A detailed map showing the changes in topography between 2012 and 2019 has been obtained through geomorphological change detection. Cracks visible in the UAV ortofoimagery were also manually traced.

Results: The most dynamic portions of the landslide are accompanied by dense micro-topographic features like secondary scarps and longitudinal and transversal cracks, which have been mapped using the orthophoto imagery. The Geomorphic Change Detection patterns are similar to a continuation of landslide activity both by enlargements and reactivations. The dynamic of some active parts of the landslide indicates that the southern part of the fortress will be affected in the near future.

Conclusions: Alongside identifying the most active parts of the landslide, we conclude that the entire recently deforested area must return as quickly as possible to the initial land use (forest). Also, from a methodological point of view, the coupling of the Geomorphic Change Detection with the other information from aerial and LiDAR sources allows the interpretation of raw change detection data.

QUANTIFYING LANDSLIDES ON RESERVOIR BANK WITH TOPOGRAPHY METER IN A MODEL EXPERIMENT

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Purpose: Scientific and objective analysis of the mechanism of reservoir-bank collapse may enrich the discipline of sediment movement and provide a basis for mitigating and preventing disaster in the reservoir area.

Methods: Using a topography meter based on structural lasers, this study quantifies the landslides on reservoir bank in a model experiment.

Results: The results show that: (1) The failure types on the reservoir-bank are avalanches, landslides and mudflows, among which avalanches occur most frequently and account for up to 73% of the total erosion events. (2) The development rates of bank cracks differ under different hydrological factors. Among them, the rainfall factor has the most significant influence, and the cracks do not stop expanding immediately after the rainfall stops. The growth rate of crack area and crack width after the end of rainfall is 0.70 times the growth rate in rainfall. (3) The soil in the water level change of abrupt slope and steep slope is the main source of erosion sediment in the reservoir area. Under heavy rainfall, the sediment contribution rate from the abrupt slope and steep slope are about 55% and 18%, respectively. (4) Heavy rainfall is one of the important triggering factors for soil erosion events on reservoir banks. The erosive and destructive effects of extreme rainfall on soil are much greater than those of general rainfall, and the high-intensity and short-duration type of rainfall is more likely to cause weakened stability of reservoir banks. The stability coefficient of bank slope under the effect of high-intensity and short-duration type rainfall is 1.48, which is significantly lower than that of general rainfall. (5) The prevention and control of reservoir-bank collapse should be "the right remedy". Different measures should be chosen for different areas for comprehensive management. It is recommended that the interception and drainage of rainfall-runoff will be the focus to prevent and control reservoir-bank collapse and that the bank slopes should be protected by the measures such as soil improvement, load reduction and counter-pressure.

Conclusions: The results may provide a reference for preventing and controlling reservoir-bank collapse in other existing or under construction large reservoirs.

ROCK DISCONTINUITY SETS IDENTIFICATION THROUGH COMBINED FIELD, REMOTE SENSING AND HIGH-RESOLUTION TOPOGRAPHIC SURVEYS

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Purpose: Proper identification of the discontinuity sets affecting a rock slope is mandatory to assess slope instability processes affecting unstable rock masses. Newly developed Remote Sensing (RS) techniques combined with high-resolution topographic surveys have demonstrated their effectiveness in the identification of rock joint sets as well as their evolution over time. However, discontinuity sets extracted from RS-derived point clouds are rarely compared with a significant statistical sample of joint orientation measurements directly acquired from the field, preventing thorough awareness of the strengths, and especially, of the drawbacks in the use of 3D digital models produced by RS techniques to analyse the structural arrangement of rock masses.

Methods: We combined the results of a traditional field survey with data obtained from a Structure from Motion (SfM) survey of a selected rock outcrop to test the use of RS-derived 3D models to identify joint sets affecting unstable rock masses. We also carried out high-resolution topographic surveys to constrain and validate the obtained point clouds, which were subsequently elaborated using a semi-automatic Discontinuity Set Extractor (DSE) to calculate joint orientation data.

Results: Field measurements collected with the traditional geological compass allowed for the identification of nine joint sets affecting the investigated rock mass. The 3D digital model construction of the rock outcrop required the acquisition of a large number of Ground Control Points (GCPs) to avoid long wave deformations of the 3D model, like cushion or barrel distortions, thus preventing erroneous reconstruction in the rock mass arrangement. The joint set extraction was observed to be strongly sensitive to some controlling parameters embedded in DSE, in particular the k-nearest neighbours (knn) and the minimum angle between the normal vectors associated with points belonging to different discontinuity sets (Angle min v ppal). In some circumstances, rock joint sets were not properly evaluated, thus resulting in unreliable, even erroneous assessments of the rock mass arrangement when compared with field measurements. Therefore, the semi-automatic extraction required the control of the user in defining the values of the key parameters controlling the analysis, which were back-calculated on the basis of the measured joint orientation data. When combining findings from samples of both field measurements and extracted discontinuities, the investigated rock mass is affected by twelve joint sets.

Conclusions: The analyzed case-history demonstrated that joint orientation data obtained from the creation of 3D models reconstructed using the RS approach is highly sensitive to both the quality of the dense point clouds and the parameters embedded in the calculation algorithms of the semi-automatic joint set extraction. The use of 3D models obtained from RS techniques has several limitations and always requires a high-resolution topographic survey (GCPs acquisition) to check the metric quality of the 3D point cloud as well as the subsequent data validation with a significant sample of direct measurements collected from the field. In addition, field measurements provide key information to calibrate and adjust joint orientation data obtained from multi-temporal RS surveys, which are aimed at monitoring the fracturing pattern evolution of the rock mass over time.

MONITORING INSTABILITIES IN TERRACED CULTURAL LANDSCAPES UNDER CLIMATE CHANGE: OPPORTUNITIES FROM MULTITEMPORAL REMOTE SENSING

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Purpose: Cultural landscapes are unique realities and witness to the evolution of human-nature interaction, often with strong rural imprint. Agricultural terraces are ancient cultivation practices that balance production with ecosystem services. An example is in the UNESCO site "Portovenere, Cinque Terre, and the Islands (Palmaria, Tino and Tinetto)". Together with villages rich in history and extraordinary natural scenery, it is characterized by a dense pattern of ancient agricultural terraces with high landscape value. However, the morphological complexity makes cultivation difficult, and field abandonment, lack of maintenance and resulting instability problems, aggravated by climate change, are common. Heavy rainfalls are frequent, resulting in landslides, floods, and debris flow. In 2011, the village of Vernazza suffered severe flooding that cost several people their lives and millions in damage. The risk of compromising the identity of the cultural landscape is significant. A tool to support risk mitigation is the monitoring of hydro-erosive processes over time. Nowadays, remote sensing (RS) technologies can provide valuable information for this purpose, thanks to frequent and low-cost data at different spatial scales. Exploiting different techniques (e.g., digital photogrammetry with Structure from Motion-SfM, Light Detection, and Ranging-LiDAR technology) and platforms (e.g., Unmanned Aircraft Systems -UAS, airplane, ground-based) is possible to obtain High-Resolution Topography (HRT) data sets and derive accurate multi-temporal Digital Elevation Models (DEM) to monitor and assess the landscape evolution.

Methods: This work focuses on the terraced slopes of Manarola, an ancient village in the UNESCO site of "Cinque Terre". We used three multi-temporal DEMs and Orthomosaics (2011-2019-2022) derived from remote sensing surveys (i.e., LiDAR and SfM). However, old “legacy” data sets and recent HRT surveys can often show comparison problems, especially when multi-temporal data regarding quality and uncertainties are not homogeneous. Therefore, an important process of error analysis and co-registration of HRT data was done to obtain accurate and comparable products (i.e., DEMs and orthomosaics) for mapping terrace collapse and instabilities, applying geomorphometric indices, and realize DEM of Differences (DoDs) to estimate the erosion process over time.

Results: The analysis of high-definition orthomosaics and the application of DoD enabled the creation of an inventory of instabilities and terrace wall collapses in the studied cultural landscape. This provides an overview of the dynamics of the instability phenomena over the years of observation and a quantification of the extent/magnitude of the terrace collapses. In addition, the cross-referencing of this information with multitemporal geomorphometric indices provided insight into the size and location of sediment source areas prone to instability, which can trigger more extensive processes like landslides, and contribute to more complex events such as debris flows. This result makes it possible to target mitigation measures for hydro-erosive processes in known critical areas.

Conclusions: Through the proposed methodology, it is possible to map areas potentially prone to instabilities over time and identify possible solutions for problem mitigation considering the risk of climate extremes. Monitoring, planning, and prevention are key concepts in making agriculture more resilient in cultural landscapes, and remote sensing technologies can be key players in rethinking protection strategies.

SESSION 2.2

INTEGRATED APPLICATION OF DEFORMATION MONITORING TECHNIQUES AND PROCESS ANALYSES OF DEEP-SEATED LANDSLIDES (part I)

MULTI-SOURCE DATA ANALYSIS TO ASSESS THE KINEMATICS OF THE PISCIOTTA DEEP-SEATED GRAVITATIONAL SLOPE DEFORMATION (SOUTHERN ITALY)

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Purpose: Although Deep-Seated Slope Deformations (DSGSD) are well-known in the literature, their evolution and kinematics are still poorly understood. Their behavior is often complex and characterized by small movements associated with steady-state creep, alternating with periods of stasis, or accelerating downslope movements that, in some cases, could result in sudden and catastrophic failure events. Therefore, a multidisciplinary approach is often required. This work shed light on the complex geometry and kinematics of the Pisciotta DSGSD, a deep-seated roto-translational sliding involving structurally complex turbiditic rock masses and interacting with man-made infrastructures. Located along the coast of the Tyrrhenian Sea in the south of Italy, the Pisciotta DSGSD has been known since the 1960s. Its movement towards the Fiumicello riverbed manifested from the second half of the eighties, with mean rates of approximately 1m/year. Significant movements affected the SS447 road, crossing the DSGSD mass at its middle height, which suffered continuous planimetric and altimetric distortions. The progressive sliding also affected the Salerno-Reggio Calabria railway tunnel, running on two distinct sediments and crossing the Fiumicello torrent (De Vita et al., 2013).

Methods: A multidisciplinary investigation was performed to reveal the geometrical features and the long- and short-term spatial and temporal behavior of the Pisciotta DSGSD. We collected structural data and Digital Surface Models (DSM) employing drone investigations. We then exploited high-resolution optical imagery and Synthetic Aperture Radar (SAR) satellite data from the Sentinel-1 satellite mission to assess the long- and short-term kinematics of the DSGSD body. The interpretation of such data has been assisted by ancillary information consisting of topographic maps at different scales, airborne Lidar data, and ground-based measurements such as rainfall data, boreholes, and inclinometric measurements. All these data were exploited by analytical and 3D numerical approaches to provide the best estimate of the DSGSD failure surface(s) and volume and assess its current kinematics.

Results and Conclusions: Typical DSGSD landforms were mapped employing in-situ surveys, aided by stereoscopic analysis of historical aerial images and high-resolution drone-based mapping. Structural data and ancillary ground-based surveys revealed the presence of a highly weathered and folded turbiditic sequence, with competent sandstone and calcarenite units alternated by weak tectonically disrupted argillite and mudrock layers. Remote sensing measurements from optical imagery and Synthetic Aperture Radar satellite data assessed the DSGSD's long- and short-term kinematics, allowing to distinguish a pre-failure period with accelerating displacement rates, a failure period with maximum displacement rates, and a current post-failure period with decelerating displacement rates. Analytical and numerical models confirmed the deep reach (up to 80 m) of the studied DSGSD, as verified by available boreholes and inclinometric measurements, and they allowed the estimation of its failure surface(s) and a volume of roughly 6.2x106 m3. Numerical modeling further revealed an apparent interference between the DSGSD and the odd railway tunnel, which intercepts the DSGSD toe for approximately 60-80 meters length.

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DETECTION AND PRELIMINARY CHARACTERIZATION OF THE ST. CYR ROCKSLIDE

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Purpose: Landslides pose a range of hazards to the safe operation of hydroelectric reservoirs due to the potential for interruption of operations and impacts to public safety. In British Columbia, Canada, BC Hydro operates a number of hydroelectric facilities in mountainous terrain, which necessitates a structured slope hazard management program. The Revelstoke Dam and its Reservoir are on the Columbia River in southeastern British Columbia. During the initial studies in the 1970's for the Revelstoke Dam and reservoir, a number of large rockslides were identified, and extensive investigations and mitigation activities were undertaken, particularly at the Downie Slide. Landslides with known displacement are actively monitored utilizing instrumentation and/or repeat visual inspections. Developing technologies that support the understanding of reservoir slope hazards are regularly evaluated and incorporated into the monitoring programs, with a recent focus on remote sensing techniques.

Methods: In 2020, a project was initiated with funding support from the Canadian Space Agency (CSA) to assess the feasibility of mapping ground deformations on the steep and forested valley walls that surround the Revelstoke Reservoir. Ascending and descending geometry C-Band (Sentinel-1) SAR data were used for a 2-dimensional analysis from 2017 to 2021. Descending geometry L-Band (ALOS-2) SAR data were tasked and analyzed over 2020 and 2021. Airborne lidar data was collected over an area identified as likely moving in the preliminary InSAR analysis. The surface morphology visible in the bare-earth lidar data was used to map "domains" with similar expressions within the slide mass. Available information was used to inform a sub-surface site investigation where two boreholes were drilled, extending through the slide surface. In-situ packer testing was carried out during drilling, and inclinometers were installed in both boreholes.

Results: The regional C-Band InSAR processing indicated clusters of points highlighting trends between 2017-2021. The L-band data clearly delineated an actively moving feature with a typical velocity of approximately 40 mm/year. The surface morphology visible in the bare-earth lidar data indicated structural controls on the moving rock mass, and four main structural domains were identified (Figure 1). A 2-dimensional assessment of the motion of these blocks was undertaken utilizing combined ascending and descending C-band data, indicating that movements were primarily downward and to the west. The two boreholes drilled in 2022 intersected sheared zones, comprised of gouge and broken rock, at depths of up to 250m below ground surface. The combined information indicates landslide volume of up to 1,000,000,000 m3 and with a projected sliding surface depth up to 250 m (extending below the reservoir level).

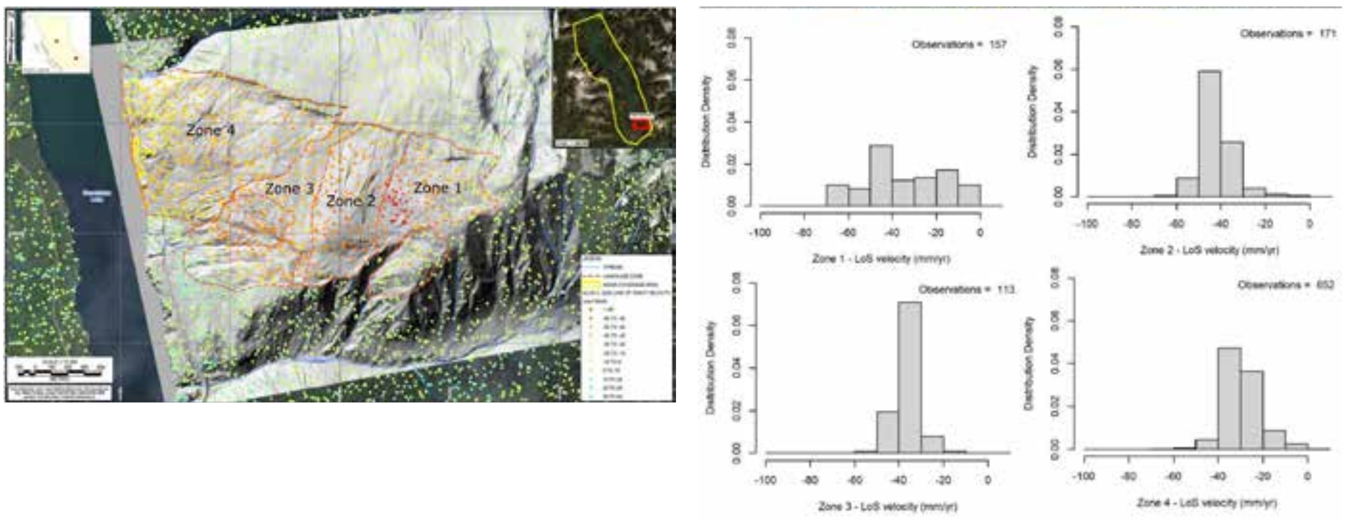

Fig. 1: 4 Main structural domains identified from lidar interpretation and L-band LoS velocities from each domain.

Conclusions: By integrating a variety of remote sensing techniques, BC Hydro was able to identify a significant rockslide that was not previously monitored along the Revelstoke Reservoir. Future work is planned to continue monitoring the slide with L-band InSAR and additional subsurface investigation. The monitoring and risk management approach will be refined over time as more data becomes available.

USING F2S3 TO ANALYSE 3D ROCK SLOPE KINEMATICS FROM POINT CLOUD DATA

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Landslides and rock slope instabilities can include a complex interaction of kinematic processes such as sliding, toppling, settling, rotating, or creeping. Distinguishing these processes to define a kinematic model of the instability is often challenging. State of the art monitoring methods have a deciding weakness when analysing the underlying kinematic process. Either they provide an area-covering information, allowing for compartmentalisation of the slope, or they provide full 3D displacement vectors. Methods such as Lidar measurements, photogrammetry or radar interferometry can cover large areas with a high resolution, methods such as GNSS- or total station measurements can track a single surface point in 3D. So far, none of these methods could provide both. However, areawide 3D displacement vectors are a key information for a complete process understanding.

We apply F2S3, a new analysis tool for 3D point-clouds, able to provide 3D displacement vectors between multitemporal point-clouds of mountain slopes in a spatial resolution of less than one meter (Gojcic et al., 2020). The basic principle of the method is comparable to that of 2D horizontal feature tracking, with the difference that F2S3 tracks the full 3D displacement of features, including their elevation shift. These 3D vectors are used to produce grids of different movement characteristics such as the displacement magnitude, the dip angle of the displacement (steepness of movement), or the displacement azimuth. In case of rockslides, we integrate the displacement values over an area or along flow paths to obtain information about the geometry of the sliding plane.

The dip angle of the displacements is highly useful and provides additional information for the kinematic analysis. Shear surfaces inducing toppling, which are invisible in traditional data analysis products, become evident by a striking, abrupt change of the displacement dip angle. Changes of the sliding plane angle or superimposing movement processes can be distinguished based on the dip angle, as can local subsidence. In combination with the other movement components, a complex, spatiotemporal analysis of the slope kinematics is possible. For simple sliding plane geometries, sliding plane models can be created, using the 3D displacements as input (Kenner et al., 2022).

The computation of dense 3D displacement vector fields using F2S3 substantially increases the information content of point-cloud analyses. Displacement processes can be differentiated, and the compartmentalisation of instabilities attain a higher level of detail. The displacement signal is less ambiguous, facilitating its geological interpretation. Spatiotemporal 3D displacement data further allow to anticipate failure events in consequence of significant changes in the slope kinematics. Moreover, the robust kinematic models allow a more accurate estimation of rockfall volumes.

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CHALLENGES IN DEFORMATION MONITORING OF SLOW-MOVING DEEP-SEATED LANDSLIDES IN HIGH ALPINE ENVIRONMENT WITH THE INTEGRATION OF DIGITAL IMAGE CORRELATION OF HIGH-RESOLUTION OPTIC AND LIDAR DATA, CONTINUOUS GNSS AND ROBOTIC TOTAL STATION: TEST SITES IN SOUTH TYROL (ITALY)

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Purpose: The Ganderberg and Trafoi landslides are complex large-scale deep-seated slow-moving landslides, located in a high Alpine environment in the Province of Bozen (South Tyrol, Italy). Due to the potential and actual damage they cause to the roads, houses, and touristic infrastructures located at their foothill, they have been thoroughly monitored for almost two decades. Periodic GNSS surveys cover nearly 15 years and highlight that both landslides are characterized by semi-continuous movements of few centimeters per year, locally up to 7 cm/year in correspondence to scree slopes fringing the main scarps. In the last three years, within the framework of the SoLoMon project, a new spectrum of data has been collected from: (a) annual airborne high-resolution LIDAR and Orthophotos surveys of both sites from 2019 to 2022; (b) in-situ monitoring by continuous GNSS (three receivers in Ganderberg and one in Trafoi) and a Robotic Total Station (RTS, in Trafoi) installed in 2022. One of the aims is to understand the challenges associated to the use of airborne data to monitor such slow to very slow landslides.

Methods: 5 to 25 cm/pixel – resolution orthophotos, hillshades and slope maps of the two landslides have been analyzed in detail. Considering all types of input data for each landslide, a pairwise comparison between the oldest and the most recent images (master and slave respectively) has been carried out through the IRIS© software (Nhazca S.r.l.). It implements advanced image-processing algorithms, allowing the measurement of long-term surface deformation driven by large slope instability. The software relies on the digital image correlation (DIC) principle (offset tracking based on optic and LiDAR datasets), and through a Graphic User Interface (GUI) it includes several operative modules such as the pre-processing, the displacement analysis, and the post-processing ones. In the displacement analysis step, Phase Correlation (PC) and Normalized Cross Correlation (NCC) algorithms, have been applied and compared aiming to find the most consistent way of measuring very slow to slow movements on a regional scale. For each landslide, a validation of the results has been carried out by comparing displacement maps, obtained with IRIS©, to measurements taken with periodic GNSS surveys on benchmarks, and through data collected by RTS and permanent GNSS.

Results: Displacement maps concerning the 2019-2022 period proved to be useful in detecting the active parts and identifying their spatial distribution over the landslide body; however, both PC and NCC algorithms tend to generally overestimate movements. With respect to permanent GNSS and RTS, which are consolidated monitoring techniques, challenges in data collection relate to operational distances and associated errors.

Conclusions: Nevertheless, especially with GNSS, results prove to be able to discriminate small movements rates within a few months from monitoring initiation, while this is more problematic with a RTS measuring prisms at more than 2000 m operational distance. This work presents the test sites and the challenges associated with integrating such techniques that, in conclusion, can be considered a useful tool for area-wide detection of superficial dynamics and point-wise precise movements measurements in such challenging mountainous context.

MONITORING EVOLUTION OF THE DEEP-SEATED LANDSLIDE IN THE LUSHAN AREA, TAIWAN, USING PARTICLE VELOSIMETRY ANALYSIS

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Purpose: The deep-seated landslide or gravitational mass movement often caused severe damages to properties and human lives. Monitoring of the landslide evolvement and movement provide important information for mitigation especially for landslide with continuous movement.

Methods: The particle image velocimetry (PIV) analysis was adopted in this study to monitor the deep-seated landslide evolvement in Lushan area, Taiwan, for the events from 2004 to 2009. Events causing ground movements and hazard in the study area include Typhoon Mindulli 2004, 0609 torrential rain in 2006, Typhoon Sinlaku in 2008, and Typhoon Morakot in 2009. The SPOT 5 level 3 satellite images before and after each event were adopted for the particle image velocimetry analysis. The ground surface variations of the Lushan deep-seated landslide during each event were obtained from the PIV analysis. Data of field investigations and global positioning system were collected for validation and comparison. Mapping of the landslide was conducted using high resolution digital elevation model and aerial photographs.

Results: Three separate deep-seated landslide masses were identified. The PIV results showed large ground surface displacements at the toe, the left and right scars compared to the mapped landslide. Field investigation found cracks developed on roads at the upper slope on the left and right scars of the Lushan deep-seated landslide in several events, and the left sliding mass appeared to be more active. Small scale landslide occurred near the toe, which might be caused by erosion of the Taluowan River at the toe. Results of PIV analysis compared well with the field data and aerial images, and it was found that ground variation coincided with the scarps of the three sliding masses.

Conclusions: Large displacements occurred near the scarp of the landslide, and left and right scars. Large displacement was also identified near the toe. From the ground variations of serial events, the evolvement of the landslide can be observed that the center mass gradually became more stable, while the left mass and right mass became more active comparatively.

ESTIMATION OF SLIDING SURFACE DEPTH FROM MULTI-FREQUENCY SYNTHETIC APERTURE RADAR INTERFEROMETRY (INSAR) OBSERVATIONS: APPLICATION TO XIONGBA LANDSLIDE, CHINA

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Purpose: Depth of landslide sliding surface is a key parameter for disaster risk assessment and prevention. The traditional landslide depth observation methods, such as ground-penetrating radar and filed borehole, focus on the limited points and are difficult to obtain the depth of whole landslide. In this context, we propose a method to estimate the sliding surface depth by processing multi-frequency synthetic aperture radar (SAR) images. Compared with the traditional methods, the proposed method could map the sliding surface depth for the whole slope.

Methods: Time series deformation in line-of-sight (LOS) direction was calculated through multi-temporal synthetic aperture radar interferometry (InSAR) techniques. In this process, the multi-frequency SAR images with different orbital direction were processed to observe the ground deformation in different angles. The relationship of geometry between SAR and slope was established based on the SAR imaging parameters and digital elevation model (DEM). After that, the three-dimensional (along-slope, cross-slope and normal-slope) sliding deformation were estimated from InSAR-derived multi-frequency LOS deformation. The mass conservation explored the relationship between ground deformation and sliding surface depth, and had been widely used in landslide volume estimation. Thus, the depth of landslide sliding surface was estimated by integrating of three-dimensional InSAR deformation and mass conservation method.

Results: A total of 290 SAR images including 140 Sentinel-1A images with ascending orbit, 138 Sentinel-1A with descending orbit and 12 ALOS-2 images with ascending orbit were collected to estimate the sliding surface depth of Xiongba landslide, China. The results showed that the deformation rate in LOS direction reached to 182mm/a. The area of Xiongba landslide was about 5.33 km2 and sliding surface depth ranged from 0 to 106.59 m, which was consistent with the field measurement results, demonstrating the reliability of the proposed method.

Conclusions: The sliding surface depth was successfully estimated through integrating of multi-frequency InSAR and mass conservation methods, which will provide useful information for disaster risk assessment, analysis and prevention.

APPLICATION OF MT-INSAR TECHNIQUE FOR MONITORING THE ACTIVITY OF DEEP-SEATED LANDSLIDE IN JIANSHI TOWNSHIP, NORTHERN TAIWAN

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The Xiuluan deep-seated landslide is located in Xiuluan Village, Jianshi Township, Hsinchu County in northern Taiwan. In recent years, this area has been affected by numerous landslides triggered by frequent typhoons and heavy rains. On September 13, 2021, the heavy rains of Typhoon Chanthu triggered slope failure again and a large volume of rock mass and debris formed a landslide dam, which continues to expand and seriously threatens the lives, property and safety of local residents. Therefore, an effective monitoring of the surface deformation of potential large-scale landslides is important to identify areas with landslide activity and is considered as a very important issue at present. Interferometric Synthetic Aperture Radar (InSAR) can acquire images that provide surface deformation data in a large scale; and has the advantages of all-weather and all-day ground observation, enabling researchers to accurately identify highly active slopes in mountainous areas for rapid monitoring. In this study, the L-band ALOS-2/PALSAR-2 radar data provided by the Japan Aerospace Exploration Agency (JAXA) were used to calculate the surface deformation using multi-temporal radar satellite interferometry (MT-InSAR) for the period of 2015-2022. The analysis results indicate that, after the rainfall event of Typhoon Chanthu, the crown of the main collapse area moved away from the line of sight (LOS) with an average surface deformation rate of between -50 mm/year to -80 mm/year; and the toes moved towards the LOS direction with a surface deformation rate ranged from 10 mm/year to 35 mm/year. The cumulative surface deformation results show that there is a significant correlation between the amount of surface deformation depending on the direction of the satellite and the amount of rainfall, especially during the wet season (June-October period) when the rate of surface deformation settlement (away from the satellite) is relatively rapid. In addition, the integrated use of the digital elevation model (DEM) and the MT-InSAR cumulative surface deformation profile can not only help researchers to understand the activity of large-scale potential landslides in the study area, but also provide a reference for future disaster prevention and mitigation works.

Keywords: Deep-seated Landslide (DSL); multi-temporal radar satellite interferometry (MT-InSAR); ALOS-2/PALSAR-2

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DEEP-SEATED LANDSLIDES' SLIDING SURFACES INFERRED USING SATELLITE INTERFEROMETRY

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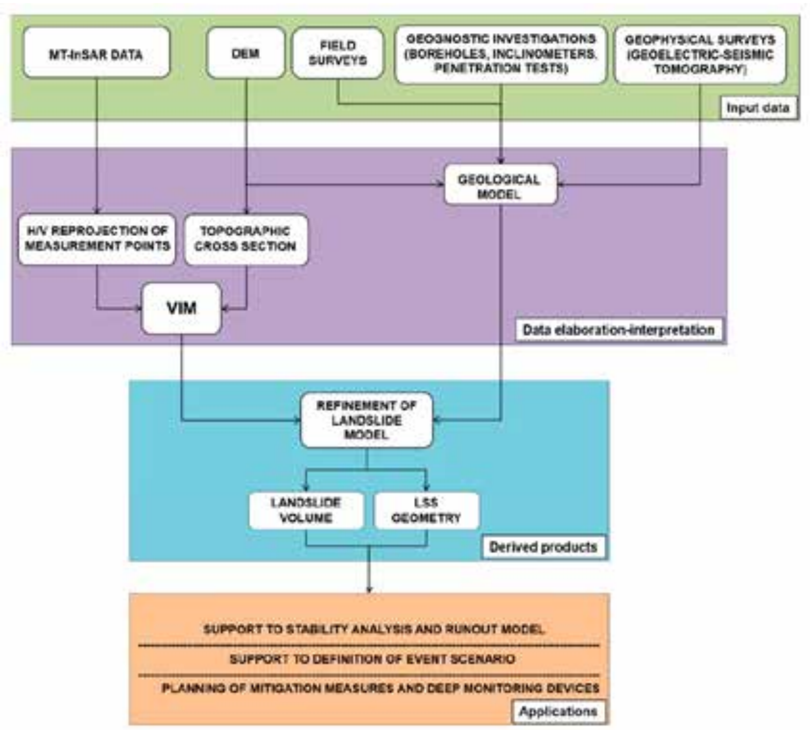
Purpose: Information regarding the shape and depth of a deep-seated landslide's sliding surface (LSS) is fundamental for the estimation of the volume of the unstable masses, which in turn is of primary importance for the assessment of landslide magnitude and risk scenarios as well as in refining stability analyses. Our aim it to validate a method to infer such information using only ground displacement data obtained by satellite interferometry and a digital elevation model.

Methods: To assess an LSS is not an easy task and is generally time-consuming and expensive. In this work, a method existing in the literature, based on the inclination of movement vectors along a cross-section to estimate the depth and geometry LSSs, is used while exploiting satellite interferometric data. Given the advent of satellite interferometric data and the related increasing availability of spatially dense and accurate measurements, we test the effectiveness of this method, here named the vector inclination method (VIM), to deep-seated landslides characterized by different types of movement, kinematics and volume. Geotechnical and geophysical information of the LSS is used to validate the method.



Results: Our results show that each of the presented cases provides useful insight into the validity of VIM using satellite interferometric data. All the cases where the VIM has been tested are in good agreement with the assumption that the mass must move as a rigid body. However, this does not mean that the LSS must be regular. In fact, VIM is able to reflect hummocks and irregularities in the LSS, as a result from vectors whose inclination does not monotonically decrease along the slope. Even landslides experiencing variation in duration and magnitude of motion along the body do not represent a problem, as VIM depends on the inclination of vectors, not on their modulus, so effects of seasonality or spatially heterogeneous accelerations do not hinder the results.

Conclusions: The main advantages of VIM applied to satellite interferometry are that it enables estimation of the LSS with a theoretical worldwide coverage, as well as with no need for onsite instrumentation or even direct access; for example, it can be a useful tool in remote areas of developing countries. However, a good density of measurement points in both ascending and descending geometry is necessary. The combined use of VIM and traditional investigations can provide a more accurate LSS model.

SESSION 4.5

ROCKFALL DATA: COLLECTION METHODS, ANALYSIS AND USE FOR HAZARD AND RISK ASSESSMENTS (part II)

A COMBINATION OF A CONTINUOS MULTI-PARAMETER MONITORING AND A PERIODIC LIDAR SURVEY: BONIFACIO COASTAL CLIFF CASE STUDY

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Purpose: France is one of the most sensitive countries to coastal erosion. In regions where the coastline is urbanized or attractive to tourists, cliffs may represent an important risk to the safety of people and property. The soft rock cliff of Bonifacio, classified as a UNESCO heritage site, located at the southern tip of Corsica is one of them. Because of the interaction of both internal (e.g., rock strength, tectonics) and external factors (e.g., weather conditions, sea erosion) this cliff is affected by both local and massive rockfalls. In the sector known as the Citadel, where the overhang is up to 20 m and where one major fracture is observed, massive rockfall hazard and risk are very high (Thoraval et al., 2021). At the request of the authorities in 2018, and as a part of large program of investigations, a multiparameter monitoring system was installed and combined with a multitemporal Terrestrial Laser Scanning (TLS) survey. Both are presented in this abstract.

Methods: A continuous multi-parameter monitoring system was designed and installed in 2019 with the objective of 1-better understanding the forcing agents and instability mechanisms with regard to the fracturing of the rock mass, and 2- monitor the cliff evolution in terms of land movements and rockfalls. This system is composed of several displacements sensors (2 multi-point borehole extensometers, 3 high-resolution clinometers, 2 crackmeters over the major fracture and 2 RTK-GPS stations coupled to a reference station in a stable area), a weather station and temperature sensors close to each geotechnical sensor. In addition, from 2018 to 2022, five TLS campaigns were carried out using a long-range scanner and a short-range scanner.

Results: Over the past three years, the geotechnical data have been relatively stable although daily and seasonal temperature variations are clearly visible in the time series. The trend of the crackmeters data is also very sensitive to the conjunction of two meteorological phenomena: a sudden drop in air temperature and heavy precipitation. Statistical analyses have shown that it is very difficult to identify the trend, the seasonality, the stationary, and the cyclical components, from time series of limited duration (less than 3 years). Nevertheless, time series forecasting seems possible. The comparative TLS analysis permits to identify volumetric changes due to small local rockfalls and to track shoreline fluctuations over time. The first LiDAR point cloud was also used to build a precise geometric model of the cliff that served as a basis 3D for geomechanical models for improving massive rockfall hazard assessment.

Conclusions: The combination of continuous multi-parameter monitoring system and multi-temporal LiDAR study can bring useful information to quantify and assess rockfall hazard as well as knowledge for long term study. Geotechnical data over the past three years mainly reflect the breathing of the cliff under the effect of climatic fluctuations. The acquired time series enable now to make projections of possible future evolution and detect unusual deviations from the trend.

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MULTITEMPORAL MONITORING OF ROCK WALLS USING TOPOGRAPHIC METHODOLOGIES AND PERSISTENT SCATTERERS INTERFEROMETRY

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Purpose: Multitemporal monitoring of rock walls is aimed at checking a study area, located in the northern area of Vecchiano municipality (Pisa, Italy) which is characterized by a morphological slope with vertical rock walls, somewhere weathered and interested by fracturing systems, prone to gravitational instability phenomena. The geological hazard of the site is conditioned also by the presence of a municipal road at slope bottom which increases the risk for pedestrians.

Methods: The rock walls were monitored by multitemporal topographic measurements carried out by Total Station (TS) using 34 prisms permanently installed on the rock walls. Among these prisms, 4 reference prisms were installed far from the walls, in areas considered to be stable over time, while the remaining 30 were located on the rock walls, in correspondence of discontinuities and on potentially unstable blocks. All the monitored prisms and targets were georeferenced by a GNSS survey carried out in static mode on 2 reference accessible points used to roto-translate the coordinates of all the targets and prisms under observation. These topographic measurements were coupled with a satellite radar imagery analysis carried out by utilizing Sentinel-1A and 1B data, in both ascending and descending orbit, lasting for 2 years period. The chosen methodology is the Persistent Scatterers Interferometry (PSI) which uses natural or artificial targets that are considered stable over time in terms of radiometric response. Theoretically, the PSI allows to evaluate quantitatively and qualitatively the possible variations in distance of individual features (pixels) along the Line of Sight (LOS) between the satellite sensor and the object on the ground. Given the morphological complexity of the site with heterogeneous vegetation distribution (shrubs and small bushes with scattered grassy areas), limestone outcrops, and the poor presence of man-made structures to be considered stable over time, three metal targets were designed and subsequently installed on the edge of the rock walls. The reason of this installation was to guarantee the presence of some artificial metal targets to be used as persistent scatterers.

Results: The TS measurements were performed every 4 months, for 2 years, with the following settings: two face measurement, for 10 repeated times at each cycle, for every prism. None of the monitored prisms have recorded significant displacements both in terms of elevation and slope distance. PSI analysis showed that the area is generally stable downstream of the monitored wall with speed along the LOS generally within the tolerances of the technique (± 2 mm/year).

Conclusions: Topographic monitoring showed that the rock walls, in the monitored time span, was stable, with no movements suggesting an imminent detachment of material. On the other hand, some anomalies in the data have brought to light how the area, where the fixed base of the TS is located, is affected by the seasonal variations of the groundwater which determine subsidence and significant oscillations of the soil level up to 6 mm. The PSI analysis allowed to assess and confirm this subsidence most probably due to the TS location on the alluvial plain.

A CAPULA BASED STATISTICAL LEARNING MODEL TO STUDY THE IMPACT OF RAINFALL ON ROCKFALL VOLUME

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Purpose: Rockfall is a major natural hazard that can pose significant threats to infrastructure and public safety. The phenomenon is often exacerbated by extreme weather conditions such as rainfall events. Inferring the intricate correlation between rockfall volumes and precipitation is of utmost importance for developing efficient risk assessment and proposing effective mitigation strategies. The paper presents a study on the uncertainties associated with this correlation and proposes a valuable statistically based approach to assess such variability and improve the prediction of rockfall events.

Methods: In the study, a copula-based joint distribution model is developed to analyze the correlation between rockfall volumes and rainfall intensity. The proposed methodology involves analyzing observed rockfall volumes and rainfall data collected along a sub-vertical rock face located in a coal mine in New South Wales, Australia. To this end, a probability distribution for both rockfall volumes and rainfall intensity is assessed for goodness-of-fit. Based on the best-fitting correlation, a copula-type distribution is developed. Finally, the joint and conditional probability distribution of rockfall volumes for a given rainfall intensity is estimated using a copula density function.

Results: The proposed model can be considered a valuable approach for assessing the probability of rockfall volume thresholds occurring following different rainfall conditions. The study emphasizes the importance of high-quality recorded data of rockfall detachments (volumes) and rainfall occurrences to build a robust data base that can support near and future hazard predictions.

Conclusions: The study presents initial results of a novel predictive approach that combines quantitative data on rockfall volumes correlated with exposure to rainfall intensity. The method represents a first step in the ongoing development of a more comprehensive framework to support geotechnical hazard practices and risk management for industry and local councils in the allocation of mitigation resources.

TOOLS FOR ROCKFALL HAZARD ASSESSMENT IN CARINTHIA, AUSTRIA - AND LESSONS LEARNED

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In Austria, legislation relating to rockfall susceptibility and hazard zoning is covered by different laws (the Forstgesetz 1975, Wasserbautenfoerderungsgesetz BGBI. 148/1985, Gefahrenzonenplanverordnung BGBl. 436/1976 and the Wildbachverbauungsgesetzt BGBl. 54/1959). The Austrian Torrent and Avalanche Control provides a hazard zoning method that defines yellow and red hazard zones for torrential and avalanche processes only. Within these hazard maps, a so-called brown hazard indication zones indicates areas that may be affected by rockfalls and other gravitational mass movement types.

The Geological Service of the Federal State Government of Carinthia is responsible to give geological assistance to the communities and infrastructure owners before or after a rockfall event. Various tools support the geologists to conduct rapid decisions and /or surveys of potentially rockfall endangered and affected areas: event database (Figure 1), hazard indication maps (Figure 2), surveys with helicopters, standardized record sheet.

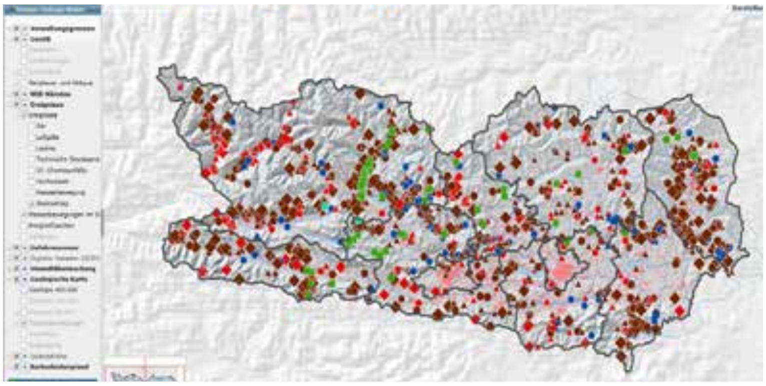

Fig. 1: Event database of the Federal State Government of Carinthia (Source: KAGIS https:\\kagis.ktn.gv.at).

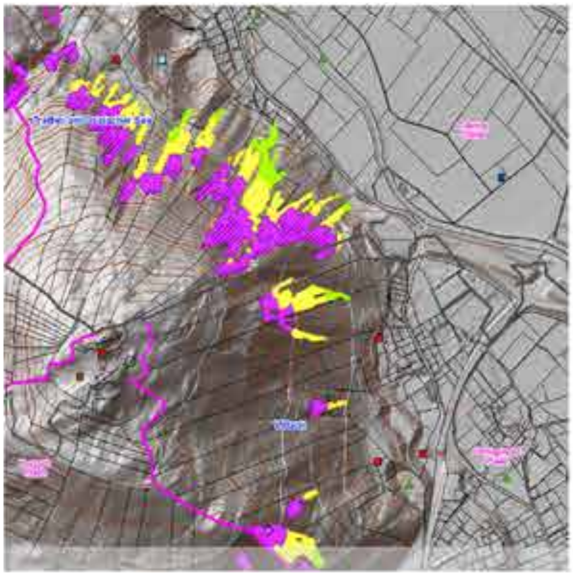

Fig. 2: Rockfall hazard indication map (Source: KAGIS https:\\kagis.ktn.gv.at

Since more than 60 years the Geological Service of the Federal State Government of Carinthia systematically collects data on different natural hazards. At present the event database contains more than 500 rockfall events. The quality (i. e. accuracy in geographic position, content) of the rockfall information depends on the method used to collect the data, data source, scope of assessment. In the frame of detailed rockfall projects (i.e. KC 32, Massmove) methods were tested to define standardized procedures for susceptibility and hazard assessments (Massmove Handbook, Melzner et al. (2009), Melzner et al. (2012), Melzner and Preh (2012)). In the period 2014 to 2015 a spatially continuous hazard indication map for Carinthia was generated in ArcGIS using a 3D costgrid model. Starting with a cliff map the runout areas were generated based on the method after Ruff 2005 (Poltnig 2015).

The scope of the present work is to discuss the applicability of the different tools for hazards assessments. Furthermore special emphasize is put to the validation of the hazard indication map with recent rockfall events.

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SALZBURG RISK ANALYSIS FOR SUBORDINATE TRAFFIC ROUTES: DEVELOPMENT OF A SOFTWARE TOOL FOR PROBABILISTIC MODELLING OF ROCKFALL RISKS

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Purpose: Rockfall hazards frequently threaten exposed traffic routes in the Alpine region. For subordinate roads and paths (municipal roads, cycle paths, forest roads, hiking trails and alpine paths) not only a hazard analysis of the potentially rockfall processes is relevant, but rather an intersection with the potentially endangered road user in the context of a risk analysis is helpful. As a result, the identified risk can be compared with the protection goals and efficient and effective protective measures can be developed. Especially due to scarce public funds for protection measures, risk assessment plays a major role with regard to the acceptable level of risk. However, risk calculation is subject to a high degree of uncertainty due to numerous variables to be included (Oberndorfer et. al., 2020). These uncertainties cannot be adequately considered with a deterministic risk calculation, since the calculation is carried out by determinants (point estimation) and not by means of bandwidths (interval estimation). Especially for the assessment of subordinate traffic routes, robust input data such as traffic counts, speed records or detailed hazard assessments are often not available. Hence, these input variables are based on expert estimates. For this reason, a software tool for a probabilistic risk calculation was developed, which takes into account the estimated values with bandwidths and thus enables a risk calculation for the individual death risk RI by means of stochastic modeling.

Methods: The software is based on the risk approach for traffic routes according to ASTRA (2012). The risk calculation comprises the individual risk of death RI (average annual probability of death due to rockfall impacts in a spatially and temporally defined hazard situation) for a particularly exposed person. The elements at risk to be considered in the risk computation are (i) pedestrians, (ii) cyclists and (iii) car occupants. The probability of death can either be calculated separately or, in the case of a shared use of the traffic route, as a combination of all three categories. Due to the different duration of the traffic use and the number of persons at risk, a weighting of the variables in the model numeric is included. The Excel-based tool uses a Monte-Carlo simulation to calculate RI. Each variable is addressed by a probability distribution using a beta-PERT distribution instead of a single value. The protection goal for the more frequently and easily accessible traffic routes is identical to the recommendations of the ÖGG (2014) with RI = 1*10-5. For the other categories, the objective of protection is dependent both on the degree of accessibility and on the grade of personal responsibility for the traffic use. Thus, lower requirements are associated to the acceptable risk level.

Results and Conclusion: The risk simulation software was tested on a case study and the results show a bias in risk using the probabilistic model compared to the deterministic approach. Thus, the individual risk for person is underestimated with the standard deterministic calculation. The potential bandwidth of the RI is represented by the probability density function. With the probabilistic simulation software, the user can select a robust safety level that sufficiently covers uncertainties in the calculation. As a result, an increased standard of safety can be applied for the assessment of the individual risk of death, especially for safety-relevant decisions. The probabilistic modeling of risk enables a comprehensible and transparent representation of the risk portfolio for a specific hazard situation and a significant gain in information can be achieved for further decision-making.

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ROCKFALL RISK AND LIFELINES MITIGATION PERFORMANCE FOLLOWING THE 2016 KAIKOURA EARTHQUAKE

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Purpose: On the 14th November 2016 an Mw 7.8 earthquake struck North Canterbury, New Zealand. Landslides and embankment failures during the event made State Highway 1 (SH1) and Main North Line (MNL) impassable both north and south of the township of Kaikōura, cutting off residents and tourists, and disrupting the main transport route from Christchurch to Wellington. Landslides and debris flows caused over 200 sites on SH1 and 950 on the MNL to be damaged. Rapid restoration of these lifelines was critical and a variety of mitigation options were used to safely re-open SH1 and MNL as soon as possible. These mitigation methods require ongoing maintenance and monitoring to ensure they are working as designed and continue to meet cost-benefit threshold, particularly as rockfall rates decline post-earthquake. This study examines the rockfall rates since the earthquake and the effectiveness of each mitigation method. A simple cost benefit analysis is conducted to determine whether ongoing maintenance provides value-for-money.

Methods: Time series rockfall data was used to examine rockfall rates throughout the study area pre- and post-installment to determine the relative performance of each method at preventing rockfall reaching SH1 and MNL over time. Risk analysis is undertaken for each mitigation method along the transport network along with a simple cost benefit analysis based on initial costs and expected maintenance costs. Time series rockfall data is analysed to determine the changing rockfall rates in order to understand when the landscape has recovered to pre-earthquake rates.

Results: Rockfall rates throughout the study area peaked in the years immediately following the earthquake (2017 and 2018), likely due to a combination of legacy damage from ground shaking and intense rainfall during three ex-tropical cyclones. However, since 2018, rockfall rates have declined steadily across the entire transport network, although remain above pre-earthquake rates as of 2023. Permanent mitigation measures have largely been successful at preventing ongoing rockfall reaching the rail or highway, with no significant instances of rockfall impacts to rail or road users reported. Unsurprisingly, avoidance appears to have been the most successful approach. In locations where alternative routes were unavailable, catch-fences appear to provide better protection than bunds, although the differences are marginal. Whilst declining rockfall rates indicate long-term maintenance of some mitigation measures may soon have costs that exceed their benefits, most options will require ongoing maintenance for some time.

Conclusions: The Kaikōura earthquake was the first example in NZ where a town has been completely isolated and the main transport route has been cut for an extended period. Results from this study will help to inform rapid mitigation decisions in future earthquake events in New Zealand, such as potential Alpine Fault or Wellington Fault ruptures. In particular, considering the longer-term maintenance costs associated with mitigation measures in parallel with slowly declining post-earthquake rates of rockfall are critical to cost-benefit decisions. Nevertheless, intangible costs associated with road and rail users perceptions of rockfall risk have not been considered, but are essential considerations for decisions on on-going maintenance.

REGIONAL ASSESSMENT OF ROCKFALL SUSCEPTIBILITY AND HAZARD IN THE EAST MACEDONIA AND THRACE, GREECE

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Purpose: In the administrative region of Eastern Macedonia and Thrace (EMT), rockfall phenomena were triggered by long and intense periods of rainfall during 2012-2022. The rockfall impacted the road network and the communities in the broader area. The goal of this research is twofold; to develop a regional rockfall inventory for EMT and to assess the rockfall susceptibility and hazard of the area, compiling the relevant susceptibility and hazard maps. The results of this study will feed future regional vulnerability and risk assessment studies for the infrastructure, people and communities in the area.

Methods: To achieve this, a rockfall susceptibility inventory was prepared from detailed fieldwork, Google Earth Imagery interpretation and previous documentation. In this study, the factors of geology, elevation, slope angle and slope aspect were taken into account in order to initially assess the rockfall susceptibility. The spatial distribution of rockfall phenomena in conjunction with these parameters were statistically analyzed based on the Landslide Susceptibility Index LSI. Weight values were assigned to each parameter to determine the influence of each factor to the occurrence of rockfalls. As a result the final rockfall susceptibility map was prepared. Subsequently, a logistic regression (LR) model was developed within the framework of LSAT (Landslide Susceptibility Assessment Tools) to evaluate the rockfall hazard of the study area. LR is used to analyze the relationship between the dependent variable, in our case occurrence or not of rockfalls, and one or more independent variables, i.e. factors of geology, slope angle, slope aspect and distance from road.

Results: The produced rockfall susceptibility map of the study area was classified in five levels of susceptibility i.e., very low, low, moderate, high and very high using the natural breaks method. Considering the four factors the LSI-based method shows that parameters of slope angle and geology are those that affect the most the occurrence of rockfalls, while parameters of elevation and slope aspect the least. From the results of the analysis 14,3% and 26,7% are classified as very low to low areas and 31,7% as moderate susceptibility class. Classes of high and very high susceptibility have comprised the 23,3% and 4% of the study area respectively. Furthermore, according to the rockfall hazard map the area was categorized into four rockfall probability classes (%), 0-25, 25-50, 50-75 and 75-100 (Figure 1). Classifying the rockfall inventory into 70% of training data and 30% of test data, the resulted rockfall probability map was validated by the ROC curve. The outcome for the area under the curve (AUC) (Figure 2) show values of >80%, which are indicating very good accuracy in the identification of rockfall probability zones of the region. Therefore, using as a guideline the rockfall hazard map, particular emphasis can be placed to the road network of the area in order to detect the most prone to rockfall phenomena road axes and consequently conduct the necessary risk and vulnerability analysis on them.

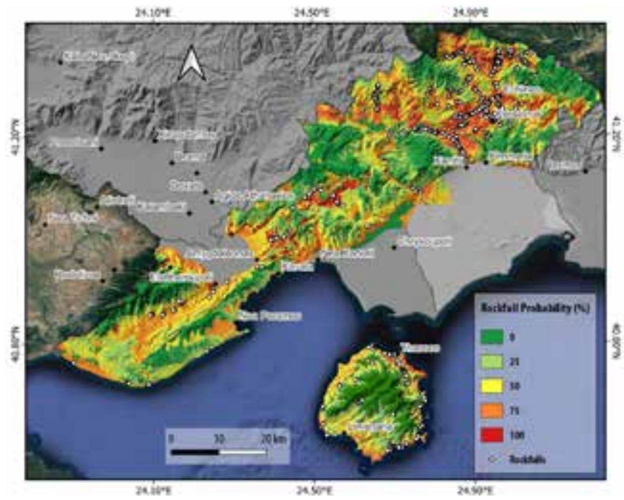

Fig. 1: Rockfall probability maps for the regional units of Xanthi and Kavala in the EMT. Lowland areas were excluded.

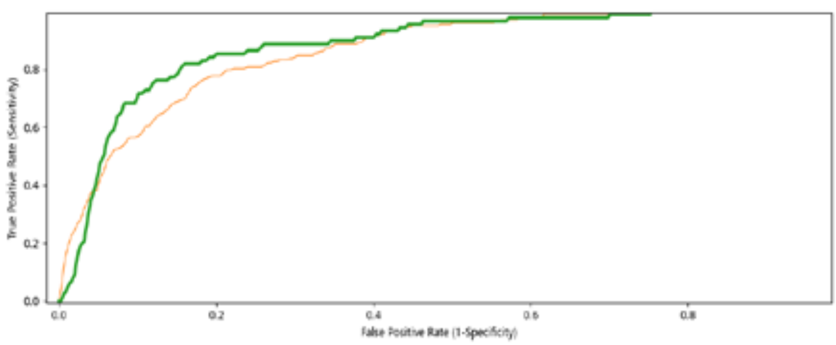

Fig. 2: ROC curves of rockfall hazard model using training (orange curve) and test-validation (green curve) data sets. The Area Under Curve (AUC) for each data set has values 0.86 and 0.88 respectively.

FROM EXPERIMENTAL QUANTIFICATION OF THE DEADWOOD INFLUECE ON ROCKFALL DYNAMICS TOWARDS ROCKFALL RISK ASSESSMENTS, INCLUDING NATURALLY DISTURBED FORESTS

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Mountain forests protect civil infrastructure against natural hazards. Predicted higher frequencies of windthrow events, bark beetle infestations, and forest fires might be reasons for higher tree mortality within forests with a protective function. The increased susceptibility to natural disturbances is also based on the widespread, unfavorable, uniform forest stand structures in alpine mountain forests. This contribution focuses on the fundamental question of whether disturbed mountain forests with lying deadwood can still protect against rockfall.

Therefore, we conducted high-end rockfall experiments on three forested sites containing deadwood. We repeatedly released artificial rocks with predefined shapes and masses between 45 kg and 3200 kg. We observed a rock energy-dependent rockfall stopping capacity of deadwood logs. Especially for cubic rocks, with roughly three symmetrical axes, the deadwood stopping capacity was higher than the one of the initial forests. Standing trees better restrained platy-shaped rocks, as they tilted on their flat side after an impact and were prone to stop completely due to the higher friction.

These results encouraged us to incorporate three-dimensional deadwood logs as obstacles into a rockfall model. We achieved a potent real-world link for new numerical modeling approaches on a broader scale. However, gaining detailed information about deadwood logs' position is time and money-consuming. Therefore, we introduce an automatic deadwood generator (ADG) to achieve additional upscaling effects and cover regional modeling scales. This relevant tool allows the realistic placement of several thousand deadwood logs based on a digital elevation model, a detailed pre-disturbance tree list, an assumed main direction of fall, and its standard deviation. We assessed thus the rockfall risk of an alpine settlement with today's observed forest and compared it with a disturbed forest, including fresh and decayed deadwood. Due to these nature-based solutions, a risk reduction for the settlement was observed. These results lead to the conclusion that rock shape and deadwood matter for rockfall risk assessments.

SESSION 3.3

RECENT ADVANCEMENT ON SLOPE STABILITY AND DEFORMATION ANALYSIS (part I)

LANDSLIDE RISK ASSESSMENT AT ROCK SLOPE AREAS FOR DESIGNING SLOPE STRENGTHENING SYSTEM

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Purpose: A landslide is a natural disaster that frequently results in economic devastation and loss of life. Malaysia, is a country on the equator, receives high rainfall yearly which increasing the risk of landslides. Various innovations and studies have been carried out to identify the risk of landslides. Malaysia's government has collaborated with many institutions to identify early risk signs of landslides. Nonetheless, risk assessment is one of the essential methods for tackling the inherent uncertainty in slope management. Therefore, the main objective of this paper is to conduct a landslide risk assessment at seven slope areas on Malaysia's East Coast that could potentially contribute to slope failure. This assessment involved an area of almost 200,000 m2 which includes both the left-hand side (LHS) and right-hand side (RHS) of the surface.

Methods: The Aerial and longitudinal photogrammetric surveys and geological mapping are used to make the assessment. Geological mapping method, such as Terrestrial Laser Scanning (TLS) were used to survey in detail on exposed outcrops on the slope to obtain related geological and geodynamic features. Geological mapping had been done to the rock outcrops and exposed soil, especially on observation of discontinuity structures.

Results: The data obtained had been analyzed to identify the dimensions of loose rock blocks and then analysis of the potential direction of rock fall can be carried out. In addition, the parameters required for the purpose of analysis of Rock Mass Rating (RMR) and Slope Mass Rating (SMR) such as intact rock strength, rock quality designation (RQD), yield profile, and water-slope groundwater conditions have been identified. There are some slopes that have cut off drains, cascading drains, and berm drains as surface drainage systems that have been built but some of these drains have been covered and filled by rock fragments. These drainage ditches that have been bent due to the pressure exerted as a result of the movement of the slope body. In addition, some obvious erosion effects shown on the slope face such as strain erosion. This erosion and instability is formed on V and VI grade weathering slopes that contain soil materials. Rough observations show that this instability is influenced by the geological structure and type of slope material. The solid and fault system in this area has caused the formation of rock blocks in the matrix of the remaining soil material (weathering grade VI). The weak zones due to these discontinuities also allow surface water to infiltrate and raise the groundwater level thus accelerate the weathering process to occur in the subsurface.

Conclusions: Overall, the evaluation of rock formations is very important to identify the level of risk before the rock slope failure occurs so that mitigation measures can be implemented so that the risk of rock slope failure can be reduced.

AN INNOVATIVE DESIGN METHOD FOR STRUCTURAL FLEXIBLE FACING WITH STEEL MESHES FOR SURFICIAL INSTABILITIES ON SOIL SLOPES

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Purpose: Design method for structural flexible facing for surficial instabilities on soil slopes.

Methods: Hybrid method.

Results: Surficial stability for soil slopes.

Conclusions: Soil nailing techniques are used to improve the stability of both natural and man-made slopes with a range of slope inclinations. They are commonly employed where the overall slope stability is deemed to have an unacceptably low factor of safety and therefore presents a hazard to adjacent land usage or where severe restrictions are placed on the land development, as examples. Generally, soil-nailed structures employ a facing selected by the designer to satisfy both structural and aesthetic requirements. Flexible structural facings are particularly suited to these applications and can provide long-term stability of the face, adequately supporting the soil between the nail locations and effectively transmitting the imposed loads of the surficial unstable layer to the soil nails. Woven double twist steel wire mesh, combined with erosion control matting is considered a flexible structural facing and has been widely used since the middle of the 20th century for soil nailing applications. Most software packages currently available utilise Limit Equilibrium Methods, where the mesh is deemed to behave as a rigid element developing the required resisting force independently of the deformations involved. On the contrary, experience has shown that this mesh can accommodate large deformations with the stabilising force exhibiting a high degree of dependence on the soil-mesh interaction and the associated displacements. The authors propose a “hybrid” approach to the design of soil nailed flexible structural facings by combining classical Limit Equilibrium Methods with an innovative displacement-controlled approach allowing a realistic estimate of the stabilizing force required by the mesh to stabilize the surficial layer of soil slopes.

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INFLUENCE OF UNSATURATED SOIL PROPERTIES AND RAINFALL DURATION ON SLOPE STABILITY: A CASE STUDY

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Purpose: To understand the influence of unsaturated soil properties and rainfall duration on the stability of Marappalam slope, Nilgiris, India.

Methods: The hydraulic response of 417.00 m long and 133.00 m high slope with an inclination of 18° to 29° was modelled based on the topographical survey carried out in the Marappalam location. The uncoupled analysis was carried out in the finite element (SEEP/W) program. The initial groundwater table was assumed to be at a depth of 20.00 m below the ground surface. Detailed field and laboratory investigations were carried out to characterize the soil properties. The unsaturated soil properties were obtained from the unsaturated soil hydraulic database (UNSODA). Three different rainfall conditions were used to study the effect of unsaturated soil properties and rainfall duration on the stability of Marappalam slope.

Results: From the field and laboratory investigations, it is found that the top 5.00 m soil consists of silty sand. The silty sand is followed by dense sand up to a depth of 15.00 m. The saturated hydraulic conductivity (ksat) of silty sand is 4x10-6 (m/sec) and dense sand is 2x10-4 (m/sec). Under the unsaturated state, the hydraulic conductivity of dense sand is lower than the overlying silty sand (Figure1). Due to the contrast in the hydraulic conductivity, the topsoil layer upto 4.00 m thick is significantly influenced by the rainfall infiltration. To understand the influence of the rainfall duration, the analysis was carried out by considering five days of antecedent rainfall followed by one-day rainfall that occurred on the day of the landslide event. The results show that at the end of the analysis, the pore pressure at 4.00 m depth increases to -22 kPa. However, it is -31kPa for the analysis considering one-day rainfall that occurred on the day of the landslide event. The variation of pore pressure with respect to depth is shown in (Figure2). Further the analysis was carried out with a prolonged rainfall of 369mm for 10 days that increases the pore water pressure to -16 kPa.

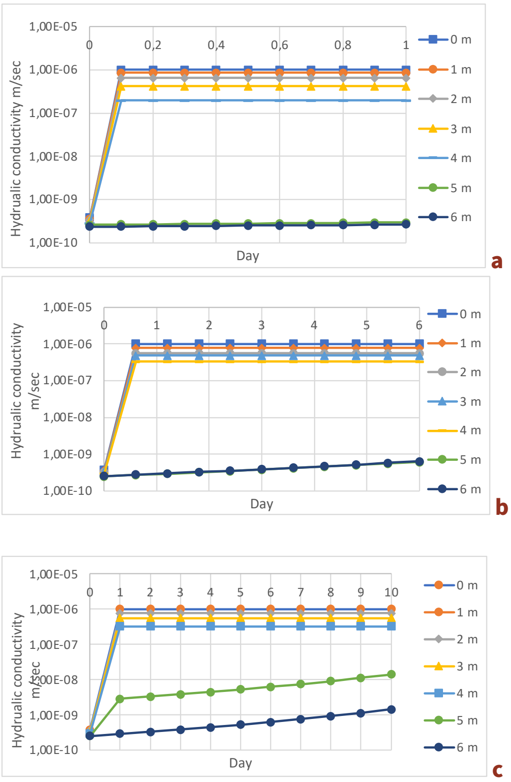

Fig. 1: Variation in hydraulic conductivity in silty sand and dense sand under unsaturated state.

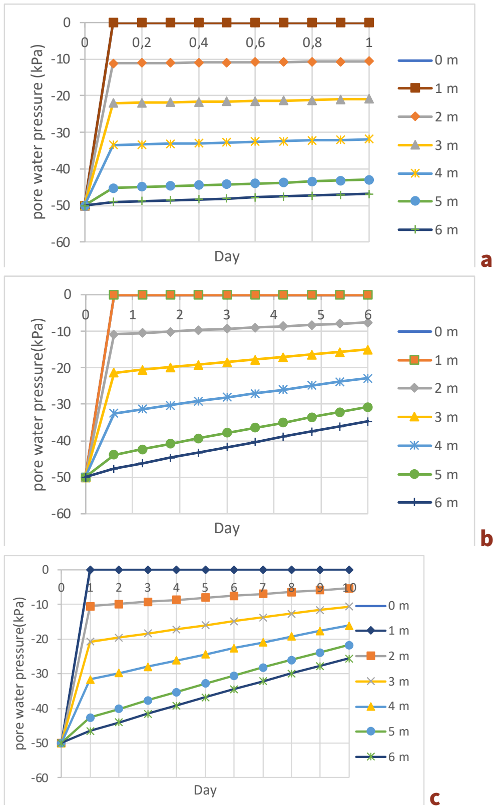

Fig. 2: Variation in pore water pressure with depth a) 1 day rainfall b) 5 days antecedent rainfall followed by 1 day rainfall c) 10 days rainfall.

Conclusions: As the hydraulic conductivity of dense sand is lesser than that of silty sand under unsaturated condition, the silty sand allows accumulation of rainwater and buildup of pore pressure due to reduction in matric suction. The development of positive pore water pressure reduces the shear strength and factor of safety, causing slope failure in the Marappalam slope. The inclusion of antecedent and prolonged rainfall shows a significant increase in pore pressure towards positive value due to reduction in the matric suction. This shows the importance of rainfall duration in the stability analysis. A subsurface drainage system shall be recommended as a suitable remedial measure to dissipate the pore water pressure.

EVALUATION OF THE STABILITY AND DEFORMATION BEHAVIOR OF PARTIALLY SATURATED CLAY SLOPES

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In this study, the stability and deformation behavior of partially saturated clay slopes were examined using 2D finite element models build in GeoStudio SIGMA/W. The numerical models were first calibrated using the results from a prior experimental study, in which small scale slopes with varying densities and geometries were constructed in a Plexiglass container before being subjected to rainfall from a specially designed simulator system. Once calibrated, the numerical models were used to evaluate the impact of rainfall intensity and duration, slope geometry and various soil properties on the stability and deformation behavior. Specifically, the numerical models were used to preform parametric studies in which the rainfall intensity and duration, soil density and coefficient of permeability were varied. Based on the results obtained, it was observed that an increase in the void ratio would result in an increase in the seepage velocity. Increases in either the rainfall intensity and duration also resulted in an increase in the seepage velocity. For a given slope inclination and rainfall intensity, the time required for the slope to become completely saturated increased with an increase in the density of the slope materials. As water infiltrated through the slope, swelling of the head of the slope was observed and the magnitude of swell depended on the void ratio and slope geometry.

EFFECTS OF SURFACE WATER FLOWS ON SLOPES

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Purpose: Surface waters can have severe impacts on natural and man-made slopes, including embankments. However, such effects are often neglected in design considerations, in operations and maintenance, and in forensic investigations. Indeed, even in specialist books on slope stability and landslides, the treatment of the effects of water on slope stability, the coverage of internal water, seepage and pore pressure far exceeds any treatment of surface water effects, if the subject is covered at all. Surface water flows have three facets of effects: erosion, transport, and deposition. Erosion has by far the largest direct impact on slopes leading to landslide through concentration at the toe of the slope in cases of coastal, reservoir, and riverbank cases. The transport phase, wherein entrainment of solids in the water is intermediate between a flow and a flood can be damaging to infrastructure such as buildings. Deposition is most important when it blocks a road or railway or actually impacts a vehicle or causes a train derailment. Other very important depositional issues are those of blockage of drains and consequent knock-on and landslide dams. The source of the surface water is obviously important and both natural and anthropogenic sources occur. Damaging effects happen when the surface water becomes concentrated, due again to either natural or anthropogenic reasons. Natural concentration problems of surface flows may result from simply ignoring the surrounding natural topography when building infrastructure. Concentration of surface flows may occur from watering-retaining engineered slopes such as dams, levees, and canals or the accidental concentration of water from blocked drain channels that subsequently get overwhelmed. Storm water runoff storage ponds provide a source of concentrated surface water and may be inappropriately sited in relation to slopes or when embankments are used to create retention ponds.

Methods: Selected case histories will be used to illustrate the effects of neglect of surface water and flows on slopes and landslides.

Results: The case histories will show the effects of surface water and provide means of mitigation/remediation for the selected cases.

Conclusions: Sustainable development of the transport infrastructure, including understanding of the effects of surface water flows on slopes, is a matter of maintaining a State of Good Repair.

SLOPE STABILITY ANALYSIS: EFFICIENT GENERATE AND SEARCH FOR CRITICAL SLIP SURFACE WITH MATHEMATICAL APPROACH

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Purpose: The efficient generation of potential slip surfaces is crucial in the stability analysis of slopes. The search efficiency of slip surfaces is mainly dictated by the degrees of freedom and space of solutions. Reducing the degree of freedom may increase the search efficiency, however it will reduce the space of solution and may not cover the critical slip surface. On the other hand, an increase of the degree of freedom will expand the solution space, but at the cost of search efficiency and is often not conducive to finding the real solution.

Methods: In this paper a mathematical approach for generating arbitrary slip surfaces in polar coordinates and spherical coordinates is presented.

Results: Two integration functions are introduced with parameter equations in two and three dimensions. Some properties of the parameter equations are discussed. We then proceed to show that these functions cover most critical slip surfaces and the search efficiency is optimized.

Conclusions: In doing so, the geometric problem of slip surface construction is converted into a parameter selection problem. Some numerical results are presented to show the advantage of our approach against conventional methods.

REALISTIC 3D MODELLING OF LANDSLIDE IN SOFT SENSITVE CLAY

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Purpose: It is a common practice to perform a 2D limit equilibrium method or finite element analysis to access safety factor of slopes with sensitive clay, leading to spurious results in many cases. The method's incapability to account for 3D effects and strain-softening in sensitive materials are major concerns. In this work strain-softening effect in a 3D domain on the computed factor of safety by comparing results of 2D and 3D calculations, was investigated.

Methods: Realistic 3D model of the 2015 Skjeggestad sensitive clay landslide created based on kriging data was analyzed under finite element framework. The elasto-plastic NGI-ADP Soft total stress-based material model was used to describe soft sensitive clay material behavior. Spatially varying undrained shear strength profile for the layer was generated by interpolating existing bore hole data. Failure was achieved by load increments combined with indirect displacement control using the arc length method. The 3D effect was analyzed by comparing results of 2D and 3D calculations. Sensitivity of factor of safety on variation of undrained shear strength profile of the sensitive clay layer, strength of dry crust resting on the sensitive clay layer and rate of softening of the sensitive clay was studied.

Results: 3D model with appropriate material parameters for various layers led to factor of safety of 0.92. Initial conditions interpolated by algorithm in terms of undrained shear strengths across the most critical section as simulated by the numerical model was compared to field observations. A 18 % increase in FoS was observed with and 18 % increase in undrained shear strength. Improper borehole data can jeopardize estimation of shear strength profile. Hence, a weightage-based algorithm was developed to cope with such uncertainties and not overestimate the stability of the slopes. Strength of the dry crust was found to drastically affect the stability of the slope. 12 times increase in brittleness of the sensitive clay layer led to a drastic 27 % reduction in factor of safety of the slope.

Conclusions: Numerical modelling of slopes in the 3D domain with an advanced numerical model capable of capturing the softening effect can serve as an efficient and accurate of predicting factor of safety. The stability of the slope was highly dependent on the spatial variation of undrained shear strength in the sensitive clay layer. Algorithm based on the method of triangulation was developed that could interpolate undrained shear strengths at unknown locations based on borehole data at known locations. Weightage could also be assigned to the boreholes in accordance with data reliability. 12 times increase in brittleness of the sensitive clay layer led to a drastic 27 % reduction in factor of safety of the slope. Calculations with various strength profiles for the crust layer, demonstrated the need for extensive field and laboratory tests to accurately estimate the characteristics of the layer as it was found to dramatically effect the safety of the slope. A 27 % reduction in factor of safety was observed for a 40 kPa drop in undrained shear strength of the crust.

SLOW GRAVITATIVE MOVEMENTS AND THEIR IMPACTS ON INFRASTRUCTURES AND BRIDGES

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Purpose: Natural slopes are often affected by slow deformations and movements, often not immediately evident. Infrastructures and bridges are quite rigid elements in relation to slope deformations so they may suffer, over long time, the consequences of these slow phenomena. The infrastructure sufferance sometimes could be evident after long time period, when it became not compatible with the performance required to civil engineering infrastructures. This is a hot topic, particularly in those areas of quite recent geological uplift, where the effect of gravitational deformations may be quite severe. Their effects are not always adequately evaluated because they difficult to be identified and modelled. They may affect also slopes where classic, as well as, advanced slope stability analyses do not returns any hazardous scenario. This work, starting from some case histories, aims at focusing the attention on such events and on their implications on the performance and safety of infrastructures.

Methods: The work critically analyse some Italian case histories of bridges affected, over time, by severe deformation. The critical analysis of the visible deformations is compared with interferometry based on satellite synthetic aperture radar images. These data are available for a limited time window, therefore the movements of slopes are not always clearly evident by instrumental data, even if are immediately evident on the base of a critical analysis of the deformations. In addition, deformations are not properly continuous, evolving at small deformations steps.

Results: The most impressive case history is the concrete bridge named Viadotto Serra close to Lagonegro, (Southern Italy). The bridge was inaugurated in 1929, remaining in service as rail bridge until 1952, when it was closed in consequence of the severe deformations affecting its second arch. Deformations slowly continued till today, evidencing the gravitative movement affecting the bridge. The long period gave the clear evidence of the slow sliding of the whole calcareous flank of the valley crossed by the bridge slowly sliding on the underlying Black Flysch. In this case, interferometry did not evidence the movement, because the bridge develops along the N-S direction. Another interesting case history is the failure of the river Magra bridge, close the town of Albiano in Northern Italy. The bridge was built in 1947 and suddenly collapsed in 2020, without evident warning signs. The critical analysis of the failure showed that the bridge was stressed by severe compressions, induced by the slow gravitative movement of the left flank of the valley crossed by the bridge. The critical analysis of the satellite-based interferometry showed a slow deformation not immediately clearly interpretable, since its velocity was comparable with the reliability of the methodology. Other impressive case histories in south Italy are presented to emphasize these phenomena.

Conclusions: The presented case histories give evidence of the presence and implications of slow slope deformation that may affect the performance and safety of infrastructures.

Fig. 1: The bridge of Lagonegro: evolution of the damage.

FIg. 2: The bridge on river Magra: the collapse and the deformation of the abutment on the left side.

SESSION 4.8

LANDSLIDE IMPACTS, VULNERABILITY AND QUANTITATIVE RISK ASSESSMENTS OF PEOPLE, COMMUNITIES, STRUCTURES, AND INFRASTRUCTURE (part II)

A REVIEW OF THE DISASTER RISK ASSESSMENT PERSPECTIVES

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Purpose: Researchers have explored different risk assessment approaches from the perspectives of different disciplines to capture urban risks, resulting in many risk assessment frameworks. In these frameworks, the risk environment is analyzed using different quantitative and qualitative assessment methods, such as fuzzy set, probability theory, and evidence theory. While each approach has introduced different risk characteristics and contributed to the area of risk assessment, there is no consensus on how these risk characteristics can be combined to establish a comprehensive framework for measuring urban risks. Therefore, this study aims to conduct a literature survey to identify risk elements from different perspectives and establish a comprehensive risk assessment framework.

Methods: A systematic review was carried out to achieve the aim of this research. The research question used for the literature review was "What approaches are being used to define and measure the impact of hazard risks in an urban environment?". The PICO (Population, Intervention, Compression intervention, and Outcome) method was used to generate the search string for the literature review by considering the keywords in the research question. Initially, 206 research papers were selected through a search strategy, and by applying a screening method, 119 research articles were selected for the detailed review. The Nvivo software was used for the review purpose.

Results: Thirty-four risk elements were identified through the literature, and a relationship graph was developed to represent the relationships among these risk elements. The relationship graph was further elaborated as a causal loop diagram with reinforcement and balancing loops to produce a dynamic risk assessment framework. The reinforcement and balancing loops presented in the overall framework presents six risk reduction strategies: 1) risk identification strategy for improve hazard recognition; 2) risk management practices to enhance risk education; 3) risk treatment strategy for hazard mitigation; 4) risk treatment for urban resilience in socio, economic, natural & built environment; 5) risk transferring strategy for urban resilience in economic and governance; and 6) risk termination strategy for urban resilience.

Conclusions: Most risk assessment frameworks do not offer a holistic risk assessment approach. The current state-of-the-art is that risks are assessed from diverse perspectives leading to different risk assessment frameworks. The risk framework presented in this paper, based on causal loop diagrams, is a powerful way of connecting these risk perspectives and producing a dynamic risk framework for assessing urban risks. The causal loop diagrams, derived from the system dynamic approach, allow the users to understand the impact of one risk element on another risk element and their influence within the entire risk framework. As a result, users are able to understand the importance and sensitivity of each risk element within a broader risk network. Furthermore, the analysis of the reinforcement and balancing loops within the overall risk network helps to understand how overall urban resilience can be enhanced through risk identification, risk education, risk treatment, risk transfer and risk termination.

THE DAMAGE CAUSED BY LANDSLIDES IN SOCIO-ECONOMIC SPHERES WITHIN THE KIGEZI HIGHLANDS OF SOUTH WESTERN UGANDA

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Purpose: Landslide occurrence is on the increase and threatens community livelihoods in the Kigezi highlands of South Western Uganda. An assessment of the socio-economic implications of landslide occurrence in the Kigezi highlands of South Western Uganda was conducted.

Methods: Detailed field investigations were undertaken with the help of local communities between June 2019 and May 2021 to identify and map recent and visible landslide scars in Rukiga uplands of Kigezi highlands. In the course of field inventories, 85 visible landslide scars were identified and mapped using handheld GPS receivers to produce a landslide distribution map for the study area. A socio-economic analysis was conducted to establish the effects of landslide damage on people's livelihoods as well as their existing coping and adaptation mechanisms. The assessment was administered through field observations and surveying, focus group discussions, key informants and household interviews as well as the use of Local Government Environmental Reports.

Results: The study established an increase in the spatial-temporal distribution of landslides over the Kigezi highlands in the past 40 years. The landslides have resulted in a reduction in the quality of land, loss of lives, destruction of transport infrastructures, settlements, farmlands, crops and other socio-economic infrastructures.

Conclusions: Therefore, it is important to look for reliable and sustainable measures to prevent landslide hazards. Total landscape reforestation with deep-rooted trees can possibly reduce the landslide risk. It is also important to undertake policy implementation for preparedness and mitigation plans against landslides in this region and in the country at large. Proper soil and water conservation measures could help in enhancing soil strength against landslide hazards.

PEOPLE VULNERABILITY TO LANDSLIDES: AN ITALIAN PERSPECTIVE ON PREDICTABILITY AND PERCEPTION

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Purpose: Frequent destructive landslides harm people every year in Italy, a country for which a comprehensive catalogue records the number of fatal landslides and the related human consequences [Guzzetti 2000 https://doi.org/10.1016/s0013-7952(00)00047-8; Salvati et al., 2010 https://doi.org/10.5194/nhess-10-465-2010, 2010; Salvati et al., 2018 https://doi.org/10.1016/j.scitotenv.2017.08.064]. Using a 16-year subset covering the period 2006-2021, we determined the dependence of the fatalities on the different circumstances of death, identifying the most hazardous behaviors in which people lost their life. The information provides real experience that can inform people awareness, based on the assumption that analyzing positive and negative examples from past events can help to cope better with future events [Stephan et al., 2017 https://doi.org/10.1007/s13753-017-0113-1; Esposito et al., 2022; https://doi.org/10.1016/j.ijdrr.2022.103440].

Methods: For the purpose, we used the information on the exact date and hour of 90 fatal landslide events and the place and circumstances in which 190 persons lost their life. We associated the fatal landslide to the forecasted daily alert level issued 24 hours before by the regional civil protection authorities in charge for hydro-geological risk. Such alerts are in four classes of increasing severity, from green to red (none, ordinary, moderate, high; https://mappe.protezionecivile.gov.it/en/risks-maps/criticality-bulletin).

Results: The analysis of the monthly distribution of the landslide fatal events reveals that, both the highest number of events (19, 21%) and the highest number of fatalities (55, 34%) occurred in October, one of the wettest months in Italy [Esposito et al. 2015 Atlante italiano del clima e dei cambiamenti climatici]. Surprisingly, when analyzing the fatal events as a function of the corresponding predicted alert levels, the lowest level of alert (green) totalized the highest number of fatal events in August. Under the same alert levels, each month suffered at least one fatal landslide. Conversely, only during October fatal landslides were recorded under all the four alert levels. The result highlights that most of the fatal landslides in Italy are not related to a level of expected criticality. Despite the great efforts made by the scientific community to implement landslide early warning systems in Italy, and elsewhere [Rossi et al., 2017 https://doi.org/10.1007/978-3-319-57774-6_24; Guzzetti et al., 2020 https://doi.org/10.1016/j.earscirev.2019.102973], and the structural mitigation measures realized under different national and regional funding and regulations, Errore. Riferimento a collegamento ipertestuale non valido.the forecast capabilities and the challenge of predicting fatal landslides remain still difficult tasks.

Conclusions: Under this perspective, the role of information campaigns aimed to increase people knowledge and increase risk perception are fundamental. Therefore, we quantify the role of the landslide risk knowledge that people perceive using the results of different national surveys on risk perception in relation to the potential landslide risk levels to which Italian people are exposed.

LIQUEFACTION OF GRANITE DEBRIS CAUSED BY UNDRAINED SHEARING CONTRIBUTING TO THE LONG-RUNOUT LUANSHIBAO LANDSLIDE IN SOUTHEAST TIBET

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Purpose: Luanshibao landslide (30°11’52.12’’N, 99°56’03.36’’E) is a paleo-landslide located in northwest of Litang county, eastern Qinghai-Tibet Plateau. The landslide initiated from a source area composed of weathered granite with an elevation of above 4,700 m. It is characterized as long-runout and a fan-shaped deposition fan whose area was about 4.4 km2. When it firstly came to light during the planning work of a highspeed railway, the range of landslide movement widely attracted researchers’ attention. Revealing the mechanism of long-runout sliding such as the Luanshibao landslide is crucial for the future project planning in similar geological environment.

Methods: Field investigation of Luanshibao landslide was carried out on 16 February 2023. Aerial survey was conducted via an unmanned aerial vehicle to obtain photos and digital elevation model. Exploratory trench was excavated on the landslide deposits (Figure 1). Samples of granite debris and riverbed soil were collected. Specimens were prepared for undrained ring shear tests to study the sliding mechanism of landslide mass.

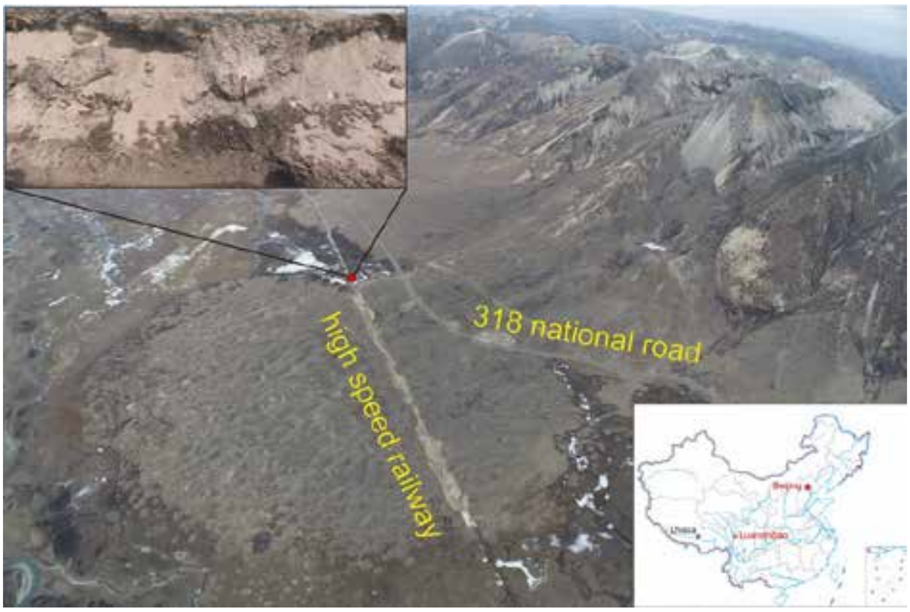

Fig. 1: Photo of Luanshibao landslide and exploratory trench excavated in deposition area.

Results: Attributed to the changeable weather on high elevation area, many fractures and joints were developed in the granite of local mountains. In front of the strongly weathered source area, the broad Litang prairie is deposited with deep soil layer. It was found in the trench that the soil deposited in valley area composed of three different layers which are humus soil layer, granite debris layer and alluvial sandy soil. Sandblasting phenomenon discovered in the front edge of deposition mass implied the high level of groundwater with local confined condition. Impacted by crushable granite debris coming from the slope, sandy layer of valley deposition is ease to be liquefied under the undrained condition caused by rapid shearing action of sliding mass, resulting in the rapid movement of the Luanshibao landslide.

Conclusions: The action of crustal uplift exposed massive fresh and intact igneous rock in the southeast Tibet. Granite surrounding Luanshibao landslide is susceptible to weathering and granite debris constitutes main component of valley deposition. Once a large-scale landslide occurred in such area, the crushable material is prone to be liquefied and participates into the sliding process as a sliding zone, leading to the fluidization and long movement distance of the sliding mass. Therefore, the amplification effect of liquefiable soil on the movement of geo-hazards should be fully considered.

RaStEM: A SUPPORT TOOL FOR PLANNING AND DESIGN LANDSLIDES AND FLOODS MITIGATION MEASURES

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In almost twenty-five years of experience gained by ISPRA in evaluating and monitoring hydrogeological mitigation measures in ReNDiS (National Repertory of hydrogeological mitigation measures - www.rendis.isprambiente.it), it has been highlitghed that designs proposed for funding do not always adequately define the characteristics of a hazard and the relationships between them and the elements exposed to risk in the area. In fact, the minimum technical contents of a design for hydrogeological risk mitigation should always make explicit and map the conditions of hazard, exposure and risk in the area where the measure is planned.

Starting from these considerations, ISPRA has developed a public web-GIS tool, freeely accessible, called "RaStEM - Standardized Representation of Mitigation Effects", through which it is possible to input in a design with standardized, clear and geo-referenced information data-set, suitable to effectively and concisely share the significant elements of landslides/floods risk mitigation designs. In RaStEM, a descriptive analysis methodology of the measures has been implemented, taking as a priority the parameters defined by the Prime Ministerial Decree (DPCM 09/27/2021) which describes the funding priority criteria applied by the Ministry of the Environment and Energy Security (MASE) for hydrogeological risk mitigation measures.

The main objective of RaStEM is to ensure that the specific purposes of a hydrogeological risk mitigation measures are always well documented in the design (in terms of reduction of the hazard, exposure and risk expected to be achieved with the measure), so that competent administrations are facilitated to make a clear assessment of the expected effects of the measure based on standardized and objectively defined elements. In relation to this, RaStEM can support designers, promoting greater attention and awareness of the mutual relationships between hazards and exposed elements, thus improving the quality of the design, nevertheless RaStEM can help administration technicians, by simplifying the presentation and evaluation of funding requests on ReNDiS.

The RaStEM methodology and tools can be divided into two distinct and coordinated methods of use, characterized by different purposes:

a) The descriptive analysis of the project aimed at representing its contents according to parameters and criteria consistent with the contents of the DPCM 09/27/2021;

b) The synthetic representation of the mitigation effects which intends to provide a parametric characterization of the measures highlighting which are the main aspects of risk mitigation.

Furthermore, RaStEM's goal is to facilitate the sharing of the essential elements of a landslide/flood risk mitigation measure among the various actors involved in planning and design, thus allowing for the systematic processing and analysis of data concerning the characteristics of the exposed elements and the expected effects linked to the implementation of the measures.

Further implementations of RaStEM are underway within the GeoSciencesIR (http://geosciences.isprambiente.it/), an innovative research infrastructure project funded by MUR (Ministry for University and Reaserch) with Next Generation EU funds.

RECONSTRUCTION OF EARTHQUAKE-INDUCED LANDSLIDE SCENARIOS THROUGH THE PARSIFAL APPROACH IN THE HIGH-SEISMICITY LAKE OF CAMPOTOSTO AREA

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Purpose: The effects of seismic activity and include secondary effects such as earthquake-induced landslides. This study aims to determine the probability of earthquake-induced landslides in the Lake of Campotosto area, in the Abruzzi region of Italy. It is an intramountain basin in central Italy, intensely felt by the 2009 L'Aquila earthquake and the 2016-2017 earthquake sequence of the Central Apennines. The peculiarity of the site is related to the presence of three dams that have created one of the most important hydroelectric basins in central Italy.

Methods: This study relies on the PARSIFAL (Probabilistic Approach to pRovide Scenarios of earthquake-Induced slope FAiLures) method, which allowed to us analyze the proneness to seismically induced earth-slopes shallow failures (of both first- and second-generation) and rock mass instabilities. The first-generation shallow landslides were thoroughly investigated using statistical models to provide a mapping of the terrain's thickness potentially involved in shallow processes. A multivariate linear regression function was developed based on linear correlations between several topographical and geomorphological factors and soil cover data collected in the field. A geomechanical survey was carried on to characterize and identify the mechanical parameters or rock slopes required for performing slope stability analysis. Existing and potential shallow landslides as well as potentially unstable rock slopes were then analyzed by means of GIS-based and Python customized scripting for performing: i) a preliminary GLE analyses (pseudo-static conditions) to get safety factor values and ii) a simplified co-seismic displacement assessment (i.e., Newmark's method) to evaluate the exceedance probability of critical displacement thresholds.

Results: The result of this study is a mapping of potentially unstable areas in hazard-defined scenarios, based on different parametric hydraulic conditions (dry, medium saturation and high saturation) and earthquake intensity with a return period of 475 years. The resulting scenarios highlighted how the soil covers more sensitive to seismic loading regardless the hydraulic conditions, while the stability rock slopes is more linked to the saturation degree of discontinuities. Second generation landslides show widespread stability up to the final scenario. In terms of interference with infrastructure, the rockslides in the most severe scenario may affect some roads. The potentially unstable slopes are mainly located on the western shore of the lake, also affecting the road. Some potentially critical areas are also present near one of the dams.

Conclusions: This study highlights the attitude of the PARSIFAL approach if combined with statistical models to provide a detailed representation of landslide scenarios. Moreover, the Lake of Campotosto case study allowed the improvement of the PARSIFAL approach for assessing earthquake-related displacements. The assessment of impact on infrastructure could be a further goal for future applications by predicting the run-out, which allows for a quantitative definition of zones that could be involved in slope instabilities.

PREDICTING RIVER BLOCKAGE, EARLY IDENTIFYING THE DAM FORMING, RAPIDLY EVALUATING THE HAZARDS OF LANDSLIDE DAM - A REVIEW

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Purpose: Outburst flood from landslide barrier lakes is hazardous to the downstream of the nature dams. Inundation upstream of the landslide dams induced casualties and properties loss as well. Since the landslide dams usually break down shortly after the formation of a landslide barrier lake, rapid responses are essential. Recently, quite a lot review papers are published and demonstrated fruitful achievements on understanding this hazardous nature phenomenon. However, few review comprehensively gathering knowledge relevant to rapid response required for emergency management. Thorough reviews focusing on available technologies for emergency management is needed.

Methods: In this study, a state of the art review focused on the issues which are relevant to emergency management related to possible short-live landslide dams including: predicting river blockage (preparedness phase), early identifying the dam forming (secure more time for emergency response), rapidly evaluating the hazards (risk) of landslide dam (upstream and downstream), and short-term measures (hard and soft ones) to mitigate the hazards.

Results: (1) Definitions of terminologies which are relevant to hazard evaluation of landslide damming lake are provided, including: (a) dam, lake, and catchment characteristics (basic information), (b) lake storage characteristics (derived information), (c) breach geometry, (d) outflow hydrograph and flood routing (e) hazards, and (f) emergency components. (2) Emergency management strategy before the landslide dam forming (preparedness) are illustrated, including (a) data collection (including landslide dam inventory), (b) susceptibility analysis, and (c) possible hazard scenarios development. (3) Technologies for early identifying the occurrence, location, and characteristics of landslide dam and related lake are introduced, including (a) landquake, (b) abnormal hydrogeological response, and (c) remote sending data. Relevant information required for emergency management is indicated, too. (4) Rapid hazard evaluation methods are summarized, including (a) downstream (stability, breach process, and flood routing), and (b) upstream (predicting the temporal variation of lake surface elevation). (5) Case histories of landslide dams are provided to enhance the critical role of rapid evaluation, from the aspects of emergency management.

Conclusions: With the quick development new technologies, rapid assessment of the landslide dam hazards soon after the formation of a landslide dam is possible for decision-making to prevent or minimize the losses.

VULNERABILITY ANALAYSIS OF BUILDINGS BY A LARGE-SCALE DEBRIS-FLOW-TRIGGERED CASCADE HAZARDS IN THE SOUTHWESTERN CHINA ON 30 AUGUST, 2020

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Purpose: Riverfront buildings often impact by debris-flow-triggered cascading hazards in deep valleys, such as the so-called multi-hazards of debris flow, dammed lake, and outburst flood. The hazard chain frequently causes huge damage to buildings located in the confluence zone. Risk analysis of buildings exposed to multi-hazards has attracted extensive attention in recent years. Accurate assessment of the comprehensive risk posed by the multi-hazards in the confluence zone requires a subjective analysis of the vulnerability. Vulnerability of the buildings strongly depends on their location relative to the confluence and the spreading of the cascade hazards.

Methods: Damage of the buildings in the confluence zone was identified by on-site survey. The channel photos and topography were obtained by an UAV (unmanned aerial vehicle). Typical cross sections were measured including muddy levels and width. Satellite image interpretation was used to geomorphic changes before and after the event. Peak discharge and velocity of debris flows was estimated by Manning-type resistance relationship. We used a numerical approach to simulate the dynamic process of the whole event.

Results: The dam-burst flood with a peak discharge of 2273 m3/s seriously eroded the debris flow fan and formed a new straighter and steeper channel. The maximum velocity estimated was 8.24 m/s and the bed shear stress was up to 853 Pa. The inundation extent of the flood in the confluence zone was enlarged by 4 times, and impact pressure increased up to 6.76 times due to the flood amplification. The vulnerability curves show a similar increase trend with impact pressure and inundation depth in Zone (II) and Zone (III), and threshold impact pressure in Zone (II) and Zone (III) at vulnerability equal to 1 is 88 kPa and 106 kPa, respectively. A vulnerability assessment chart has been developed, and three categories, namely slight damage (0.3-0.4), moderate damage (0.6-0.7), and heavy and complete damage (0.8-1.0) have been divided. Heavy damage occurs at impact pressure greater than 40 kPa, and slight damage occurs below 20 kPa. Moderate damage occurs at impact pressure between 20 KPa and 40 kPa.

Conclusions: This study investigates in detail a catastrophic debris flow and dam-burst flood occurred in Niri River, Ganluo County, Sichuan Province, southwest China on 30 August 2020, in order to provide a subjective function of the vulnerability of the buildings in the case of multi-hazards. Three hazard zone based on the damage pattern of the building has been divided: (I) buried by primary debris flow; (II) inundated by secondary dam-burst flood; (III) buried by debris flow and inundated by dam-burst flood sequentially. Vulnerability curves in Zone (II) and Zone (III) have been developed using the impact pressure and inundation depth, and a vulnerability assessment chart with three damage categories was presented. The research fills the gap in multi-vulnerability assessment for the debris flow hazard chain and is helpful for disaster mitigation in the confluence area.

QUANTITATIVE RISK EVALUATION OF LANDSLIDES ALONG HIGH-VOLTAGE POWER TRANSMISSION LINE, A CASE STUDY FROM THREE GORGE RESERVOIR, CHINA

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Purpose: The high-voltage electricity transmission line is a critical component of the national energy network in China. However, due to the complex terrain, the tower foundations are often at risk from landslides, which may cause significant damage to the electricity network. Therefore, reducing the damage to transmission towers from extreme weather and landslide hazards is crucial to improve the safe operation of the regional power grid. Despite this, there has been a lack of research on landslide disasters for transmission towers, particularly in terms of quantitative vulnerability studies. As a result, it is imperative to carry out risk assessment research of geological disasters for the purpose of power grid disaster management. In this study, a framework for quantitative risk evaluation of landslides linked to electricity transmission towers was proposed.

Methods: The risk assessment formula proposed by Yin (Yin K et al., 2016) takes into account indirect risks, which is consistent with the loss characteristics of the power grid. To establish a landslide risk assessment model applicable to transmission towers, it is necessary to first analyze the landslide hazard. The hazard analysis of the landslide considered the impact of different rainfall amounts on the landslide, and calculated the probability of failure for both the landslide as a whole and the area of the landslide where the transmission towers are located. The existing standards consider inclination as the criterion for deformation of transmission towers. Therefore, this study proposes a quantitative vulnerability analysis method based on the inclination of the tower. Based on numerical simulation and the relationship between ground deformation and transmission tower inclination, a vulnerability curve for transmission tower was developed using Weibull distribution, which is commonly used in reliability engineering.

Results: The results of the hazard analysis indicate that the landslide as a whole is quite stable. Nevertheless, the area of the landslide where transmission tower is located may instability during periods of extreme rainfall. Therefore, quantitative risk assessment of transmission towers is highly necessary. The accuracy of the transmission tower's vulnerability curve was verified by actual monitoring results. The risk assessment results show that the potential indirect risks of tower damage are much higher than the direct risks.

Conclusions: This study established the vulnerability curve of transmission towers, which allows for a rapid evaluation of the status of transmission towers on slow-moving landslides, enabling timely maintenance and repair measures to be taken for towers in danger. The study also evaluated the direct losses caused by mountain landslides that may damage the structures of electricity facilities, as well as the indirect losses caused by secondary consequences. This may be a useful reference for disaster prevention and reduction work in the power grid and other types of indirect risk assessments.

SESSION 2.4

MULTIPLATFORM AND MULTISENSOR APPLICATIONS FOR LANDSLIDES CHARACTERIZATION AND MONITORING (part II)

INVESTIGATION OF SLOW-MOVING LANDSLIDES IN THE NORTHERN APENNINES (ITALY) BY MEANS OF INTEGRATED TECHNIQUES

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Purpose: In mountain environments, landslide activity can be assessed through different remote and proximal sensing techniques at different scales of investigation and the combination between them. The complementarity of different methods and techniques and the synergistic use of the data collected can be crucial for landslide recognition and monitoring. The aim of this study is the investigation of slow-moving landslides in the Scoltenna valley (Northern Apennines, Italy) through an integrated methodological approach that combines remote and proximal sensing techniques. The study area is widely affected by active and dormant landslides which are the dominant geomorphological process in the valley.

Methods: The investigation involved satellite interferometry (InSAR) analysis, global navigation satellite systems surveys (GNSS), aerial photogrammetry based on the use of uncrewed vehicles (UAV), and terrestrial laser scanning (TLS). In addition, repeated geomorphological field surveys and geomorphometric analyses were performed. Three active landslides were studied in detail and monitored through time in order to detect their state of activity and monitor their evolution. Historical aerial photos from Regione Emilia-Romagna Web Map Service and high-resolution satellite images from Google Earth were also analysed. All data were organized in a multitemporal perspective, referred to the same georeferenced system and implemented in a Geographic Information System (GIS) environment.

Results: The application of this integrated methodological approach detected centimetric displacements at the three investigated sites (La Confetta, Ponte Olina and Sasso Cervaro landslides) and highlighting that the most significant displacements through time appear at the foot of the landslides where interaction with fluvial activity takes place.

Conclusions: The combination of various innovative techniques of remote and proximal sensing proved to be a useful tool for the assessment and analysis of surface deformations and, more in general, for the investigation of slope processes. The integration of data collected from different methodologies (InSAR, GNSS, UAV photogrammetry and TLS) overcame the limitations of each technique and allowed the validation of the results obtained.

THE PATHFINDER PROJECT: A SCALABLE FLEET OF DRONES FOR LANDSLIDE MONITORING AND CONTEXT AWARENESS

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Purpose: The aim of the PATHfinder project (PNT as A TecHnology to support a scalable Fleet of lINked Drones operating for preventive monitoring and EmeRgency missions) is to design and implement a cooperative system for challenging scenarios (difficult access and wide extension), with a large data flow generated by different sensors that may be used in parallel, with real-time and timely delivery information of the observed scenario, suitable for persistent surveillance, monitoring, emergency management and for the adoption of proper measures in response to severe disasters.

Methods: A solution based on the usage of a scalable fleet of master tethered drone (MTD) /aerial drones (AD)/ underwater drone (UD) / ground rover (RD) drone has been implemented. PNT (positioning, navigation, and timing) technology plays an important role to support the missions performed by the fleet of drones on site. In particular: the AD, UD and RD drones will be equipped with high-end and low costs GNSS receivers under test with PNT algorithms. Moreover, an independent communication infrastructure is built-on where the MTD is deployed: an accurate positioning/attitude configuration acts as core node embarking directive antennas.

Results: To test and validate the functionality of the proposed solution, the Stromboli Island (Sicily Region, South Italy) has been used as validation campaign. The Stromboli volcano is active from more than 20.000 years and the resulting volcanic scenario is complex and challenging also due to the combination of different sources of hazard. The Stromboli Island, given its persistent activity, has slopes prone to landslides with possible generation of landslide-induced tsunamis affecting populated areas in proximity and along the Southern Tyrrhenian Sea coasts. In particular, the PATHfinder solution has been tested along the northwest flank of the volcanic cone, i.e., the so-called “Sciara del Fuoco”, a depression originated by a series of major lateral collapses in the last 13.000 years and where instabilities affect both its submarine and subaerial sectors.

Conclusions: A solution based on the usage of a scalable fleet of drones (master tethered, aerial, underwater and ground rover) has been designed, implemented and tested, providing situational awareness solutions, early warning and persistent surveillance during disaster recovery and emergency response scenarios. The proposed configuration allows to significantly extend the on-field area coverage for quick monitoring and surveillance, increasing the availability of a reliable positioning service and ensuring first responder safety.

REMOTE SENSING BASED MULTISENSOR AND MULTIPLATFORM CHARACTERIZATION AND MONITORING OF LANDSLIDE ACTIVITY IN SOUTHERN KYRGYZSTAN

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Analysis of spatiotemporal landslide evolution within large areas is important for understanding landslide process dynamics at regional scale and thus prerequisite for probabilistic hazard and risk assessment. Many regions in the world lack systematic assessment of landslide activity resulting in absence or incompleteness of landslide inventories. In such data-scarce regions, remote sensing techniques have a great potential in deriving process information in high spatial and temporal detail. Satellite remote sensing data allow systematic spatiotemporal monitoring of recent landslide activity and reconstruction of backdated landslide activity based on satellite data archives covering a time period of about four decades by now.

These globally available datasets also form a great basis for detailed ground-based investigations of landslides including UAV surveys which allow very detailed 3-D assessment of landslides and precursors for their further evolution, such as crack formation. Thus, the available techniques and data enable multi-scale landslide investigations covering different spatial extents and time periods. For this purpose, we have developed a number of tools centered around a (semi-)automated approach for spatiotemporal landslide mapping using satellite time series data of various multispectral sensors.

We demonstrate the application of this approach to an area of ongoing high landslide activity in Southern Kyrgyzstan which is situated along the Eastern rim of the Fergana Basin. Although this region is known as the most active landslide prone region in Kyrgyzstan, it lacks regular systematic assessment of landslide activity. Our results comprise monitoring of recent decadal landslide activity (2009-2019) for an approx. 12,000km^2 large area and retrospective analysis of long-term landslide activity extending the formerly observed time period back to 1986 for a 2,500km^2 subset. The derived multi-temporal landslide inventories contain several thousands of landslides, ranging in size from 50m^2 to 2km^2 affecting a total area of 45 km2. We also derived spatial activity clusters and their shifts over time forming the basis for further analysis of their relationships to predisposing and triggering factors.

The resulting information on multi-temporal landslide hotspots also formed the basis for more detailed investigations in some of these areas in form of UAV surveys which were conducted in the years 2016 and 2017 whereas the latter one represents the year of highest ever observed landslide activity in this region. We surveyed 12 landslides using DJI Phantom Pro 3/4 drones. We analyzed the potential to estimate landslide volumes using post-failure UAV-surveys only.

For this purpose, we compare the UAV DEM with all globally available DEMs and exploit image reconstruction methods making use of stable areas around the occurred landslide in order to account for local uncertainties in global DEMs allowing a more robust estimation of landslide volumes. We also investigated the potential of multi-temporal UAV surveys for crack monitoring in the head part of the landslides as indicators for future reactivations. Putting the results of the short-term UAV surveys in the context of long-term satellite-based analyses provides us deeper insights into landslide evolution and dynamics at different temporal and spatial scales forming the basis for objective multi-scale landslide hazard and risk assessment.

INTEGRATION OF REPEATED LIDAR-ORTHOPHOTO SURVEYS AND ROBOTIC TOTAL STATION FOR THE ASSESSMENT OF COMPLEX MOVEMENT PATTERNS IN LARGE-SCALE EARTHSLIDES - EARTHFLOWS: THE CORVARA LANDSLIDE (SOUTH TYROL)

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Purpose: Large-scale active earthslides-earthflows are characterized by spatially and temporally complex displacement patterns. For instance, movement rates can vary significantly inside the landslide area, with some parts moving up to meters per year and others just a few centimeters. Furthermore, displacement rates can change significantly throughout a year or longer, in response to meteo-hydrologic forcing factors. Thus, the characterization and monitoring of large-scale earthflows can be optimized only by the integration of different survey and monitoring techniques, i.e., by using distributed detection methods to grasp the spatial pattern of active slope processes and multipoint continuous monitoring systems to get an insight in the response of slopes to forcing factors.

Methods: Many techniques have been developed and implemented over the years for landslide monitoring, spanning from field-based methods to aerial and spaceborne ones. Nevertheless, not all the techniques are equally suitable for the analysis and long-term monitoring of active earthflows. Typically, InSAR techniques suffer from the lack of persistent scatterers on the ground or decorrelation due to high movement rates, while inclinometers can be out of range of operation within few months or years and permanent GNSS receivers cannot be placed in the most active areas, as they can rapidly be knocked down by movements. Within the framework of the SoLoMon project, Repeat Lidar-Orthophoto Surveys (RLOS) and Robotic Total Station (RTS) have been integrated to assess the spatial and temporal variability of slope movements in the Corvara earthslide-earthflow (Corvara in Badia, South Tyrol).

Results: The spatial-temporal variability of movements in this landslide has been revealed by more than two decades of periodic GNSS surveys, that have shown how movement rates range from a few centimeters per year in the toe zone to up to tens of meters per year in the most active track and source zones. Nevertheless, periodic GNSS does not have the spatial and temporal seeding to picture the distribution of movements over the entire slope nor their variation at weekly to daily scales. Beyond periodic GNSS, the landslide had been monitored since 1997 with many other techniques, including inclinometers, InSAR (including MTI and Offset Tracking with corner reflectors) and some continuous GNSS devices. Nevertheless, these techniques showed shortcomings with respect to durability, spatial coverage, maintenance, time, and effort for surveys, being problematic for the long-term sustainability of monitoring, which is in turn one of the objectives of the SoLoMon project. Specifically, RLOS with centimeter level of accuracy have been acquired in 2019, 2021, 2022, and Digital Image Correlation (DIC) analysis of high resolution orthophotos, hillshades and slope maps has been carried out with IRIS software (Nhazca S.r.l.).

Conclusions: DIC analysis proved to be effective for the assessment of the spatial distribution of the most significantly active areas within the landslide area. At the same time, continuous monitoring of movements with the RTS, which has started in 2022, has already shown that the landslide movement rates are modulated in time, responding to changes in meteo-climatic conditions. Undoubtedly, these results are of high added value for the characterization of such a complex phenomenon.

A NOVEL APPLICATION FOR REMOTE LANDSLIDE MONITORING

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Purpose: Landslides are hazardous phenomena which may cause significant impacts to human infrastructures, partial or total destruction of environmental settings as well as to human life (Peduto et al. 2017). Landslide monitoring thus becomes a necessary tool to investigate the kinematic behavior of a phenomenon and the related displacement, identifying: the predisposing and triggering factors; ii) the actual state of activity iii) the landslide evolution. Landslide monitoring can be performed through different approaches: i) conventional in situ monitoring techniques (inclinometers, extensometers, GNSS); ii) remote sensing techniques (terrestrial or air/spaceborne sensors). In this work, the state and distribution of a roto-translational landslide activity was monitored, combining data from multi-temporal field surveys, 3D models of the slope and IR images, resulting from the airborne application of RGB and IR thermography. Thermal anomalies detected during different monitoring campaigns allowed to recognize kinematic features, such as forming cracks, developing scarps, wet terrain portions, and loose material. Field surveys confirmed that the location of thermal anomalies well corresponds to real structures on landslide body, hardly detectable by RGB surveys. The landslide monitoring time span was about 1 year, monitoring the different phases of its kinematic evolution.

Methods: The studied landslide is In Borgo Priolo (PV) municipality, located in the northern termination of Italian Apennines. Airborne and field surveys were carried out in 6 different times, both with RGB and IR cameras, to retrieve high-resolution orthoimages and Digital Surface Models (DSMs) in different periods of landslide activation. From DSMs were retrieved and processed the landslide main morphological evolution in time (slope angle, profile and planar curvatures, slope aspect). The acquisition of thermograms was performed both before dawn and after sunset, to reduce the influence of the solar radiation leading to shadow effects and non-uniform surface heating. In-situ surveys were performed to validate results from airborne observations, by measuring, on field, the kinematic features and their evolution.

Results: From the morphological analysis (DTM) landslide structure and kinematic elements were retrieved, as well as their evolution. The DSMs differences enlighten the landslide activation periods. The qualitative analysis of thermograms confirmed the correlation between thermal surface anomalies and features or elements occurring at the landslide area. Thermal slope profiles allowed a quantitative analysis, achieving a good definition of the main features involved in the instability process.

Conclusions: This work confirmed the reliability of a novel application that combines photogrammetry and IRT for landslide monitoring. Multitemporal surveys allowed to characterize and monitor a landslide affected by a retrogressive and enlargement trend, being a suitable option when there is not the possibility to monitor through in-situ instruments.

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RAPID DETECTION OF LANDSLIDE AND SLOPE SURFACE MOVEMENT BASED ON CHANGES IN INTENSITY USING GROUND-BASED SURVEILLANCE CAMERA IMAGES

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Purpose: The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has been increasing the number of closed-circuit television (CCTV) cameras installed to monitor important points along rivers channels with salient landslide areas imminently or largely impacted, and where critical mitigation facilities are located. Thereby local situation can be monitored during major events as typhoons. Besides regular CCTV cameras, post-event installation as a quick response becomes more and more common. On-site images are shared through satellite communications and other networks to Headquarter. We aimed to develop a detection method, agile and practical, for landslide and surface movements. Advanced learning methods are widespread these days, but they are too demanding and judged impractical in regard to computational power requirement. The practicality is essential in applying them to a large number of CCTVs. Realistic compromise can be attained by utilizing existing video data stock of past major landslide-related phenomena without degrading the quality.

Methods: We focused on the fact that a significant slope surface movement caused a major change in the monitored image and dag deep into a detection method that sets a threshold value for the difference in luminance value time-wise, chronologically. In addition, a device was created and operated using actual monitoring images, and the contents of errors (false positives) were sorted out (Figure-1 - Figure-2).

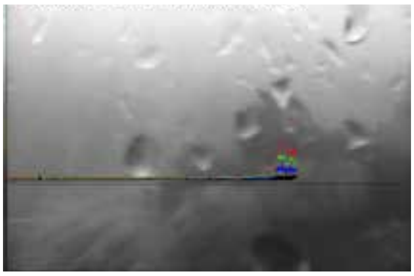

Fig. 1: Example of analysis using deep-seated landslide (recollapse) video.

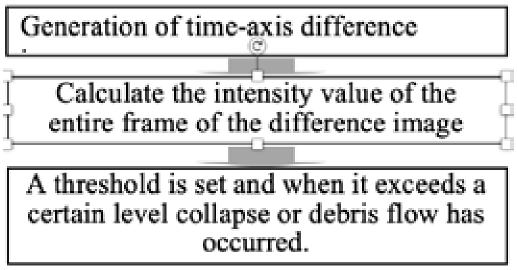

Fig. 2: Detection method of collapse and debris flow by difference of brightness.

Results: A device was created and operated using actual surveillance video, and the contents of false positives were sorted out. False positives were caused by short-term movements that were not major landslide movements, brought by: wiper insect, test signals, etc. As a correction, the time interval of index of luminance difference was widened. Corrections to false positives caused by sunlight incidents on the luminance value threshold were also incorporated to lessen the impacts by a range of luminance values above a certain level. For false positives caused by cloud shadows movements, determination of the image's texture based on the average area of the black-and-white binarization seemed effective. Furthermore, the study of the causes of false positives in a test operation revealed that many were caused by sunlight illumination due to cloud motions, so correction by way of pattern matching and setting seemed adequate, upon adjusting their thresholds.

Conclusions: A method focusing on the luminance difference value was proposed as a method for practical detection of sliding mass on hillside slopes, whose computational requirement remains reasonable. Addition of simple error corrections rendered the number of false positives saliently low to a few per day. The method is practical and can presumably be applicable to a large number of surveillance images.

SESSION 3.4

PHYSICAL AND NUMERICAL MODELLING OF LANDSLIDE-STRUCTURE-INTERACTION (LSI) (part II)

INVESTIGATION OF FLOW-BED-BARRIER INTERACTIONS IN DUAL FLEXIBLE BARRIER SYSTEMS: PHYSICAL MODELLING

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Purpose: The most distinct feature of debris flows in contrast to other landslide types is the potential to entrain bed sediments through complex flow-bed interactions, leading to large accumulated flow volumes and mobility. Of particular interest for the designers of debris flow arresting barriers is how these flow-bed interactions influence the debris flow impact dynamics. In the recent decades, multiple flexible barriers have been utilised to intercept debris flows, as an effective alternative to single rigid barriers with a large size. Flexible barrier ring nets are erected spanning across the width of debris flow channels at multiple locations along probable flow paths. After the initial impact of the flow front against a flexible barrier the excess flow material follows an overflow trajectory and lands on the downstream channel beds consisting of erodible bed sediments. Depending on the instantaneous compressive force induced by this landing flow material and the contractive shearing of the bed material, excessive positive pore pressures can be generated within the bed leading to bed fluidisation and entrainment. Despite this higher erosive capacity of overflowing material landing on erodible beds, the existing design of multiple barrier systems overlooks the effects of flow-bed interactions resulting in non-conservative estimates.

Methods: In the current study, unique physical flume tests are conducted with debris flows impacting on dual flexible barriers in a state-of-the-art 28-m-long flume facility in Hong Kong. The flume has a rectangular uniform cross-section with a width of 2 m, depth of 1 m and an inclination of 20o. The first flexible barrier is 0.8 m in height and erected 6 m from the gate. The second flexible barrier is 1.5 m in height and 4 m in width and erected at the end of the horizontal runout zone. The flume base between the two flexible barriers is modified to include a wet erodible bed with 8.5 m length and 0.2 m thickness to investigate the landing induced entrainment mechanisms. Tests are conducted using 9 m3 of debris flow volume for flume base with the erodible bed section and compared with the control test without the erodible bed section. Instrumentation such as high-speed cameras, wide angle cameras, unmanned aerial vehicles (UAV), laser and ultrasound sensors (for flow depth measurements), basal normal and shear load cells, basal pore pressure sensors, cable load cells (for flexible barrier impact force measurements) and erosion columns (for erosion depth measurements) are used for acquiring data for analysis.

Results: To identify the effects of flow landing on the erodible bed overflow distance, landing angle and the landing influence zone are correlated with the erosion spatial pattern. The bed fluidisation is quantified using the measured landing induced stresses on the erodible bed. Furthermore, the impact dynamics at the second flexible barrier is compared between the control test and erodible bed test, to quantify the effects of flow-bed interactions on second barrier design.

Conclusions: The findings offer new insights into the importance of incorporating landing induced entrainment mechanisms for the design of multiple barrier systems.

MODELLING FLOW-LIKE LANDSLIDES INTERACTING WITH DIFFERENT STRUCTURES

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The impact of flow-like landslides against rigid walls, obstacles, barriers, and similar types of protection structures, has been attracting the interest of practitioners and scientists since decades. There is in fact the practical challenge to adequately design such structures. In doing that, the inner complexity of flow-like landslides must be considered. The evaluation of the impact forces against obstacles remains difficult especially if the solid-fluid interaction within the flow is considered. In addition, flow-like landslides are often characterized by large deformations, which depend on slope geometry, soil type and triggering mechanisms.

Within a framework of landslide risk mitigation, we may assume that an impacted structure can undergo: i) limited damage to non-structural elements, ii) damage to the structure (with eventual partial destruction), iii) collapse. The occurrence of any damage scenario and its severity is the outcome of different factors combined. The type of urbanization (dense or sparse), the construction features (type, materials, age, etc.), the exposure (direct or limited) to the impact, the type of impact (frontal or lateral), and other site- or case-specific features. Thus, the assessment of potential damage to a structure requires analyses and zoning at detailed scale.

A Mechanically Stabilized Earth (MSE) wall is employed in this study as an alternative protection structure to mitigate the risk associated to flow-like landslides. In the context of landslide protection, they are also called Deformable Geosynthetics-Reinforced Barrier (DGRB), as they are composed of granular soil and geosynthetics reinforcement elements, such as high tenacity polyester (PET) geogrids. These geostructures have been formerly investigated to reduce the runout (and the potential damage) of flow-like landslides, while they are typically used as deformable barriers against snow avalanches or rockfalls.

What is really challenging is to find a mathematical framework to properly describe the so different materials and behavior of both (i) the flow-like landslide and (ii) the impacted structure. An advanced numerical code based on Material Point Method (MPM), i.e., the Anura 3D code (and related developments done by Deltares) is used thanks to its capability of considering the coupled hydro-mechanical behaviour of the propagating mass and simulating large deformations and displacements (with no restriction), that are typical features of both a flow-like landslide and a structure under severe external loads such an impulsive impact. The proposed approach can be also extended to other types of structures, such as Reinforced-Concrete (RC) wall and framed buildings.

The numerical MPM-based modelling of the interaction between a flow-like landslide and a DGRB outlined that landslide pore-water pressure largely increase in the early stages of the impact ($t < 1s$), while reducing later dependent on landslide deformation plus propagation and related also to the displacement plus deformation of the protection structure. The excess pore water pressure generated during the Landslide-Structure Interaction (LSI) is proved as an important mechanism contributing to landslide run-up, overtopping and structure displacement or disruption until failure or unserviceability condition.

A SMOOTHED PARTICLE HYDRODYNAMICS METHOD FOR MODELLING THE DYNAMIC IMPACT OF DEBRIS FLOWS AGAINST OBSTACLES

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Purpose: Flow-like landslides, such as rock avalanches, debris flows, mud flows and so on, always destroy the surrounding infrastructure and threatens the life and property safety of the downstream inhabitants. Various types of obstacles such as check dams, rigid walls, flexible barriers, and filter dams have been installed along the examined flow path to avoid these potential risks. A key issue in designing and implementing mitigation measures is to determine the impact force acting on obstacles. In the last few decades, due to the advancement of high-speed computing programming, numerical modeling techniques on landslide related research have shown a significant evolution. As a result, we can do a clear understanding of the interaction mechanisms by numerical approaches.

Methods: In this paper, the weakly compressible Smoothed Particle Hydrodynamics method is used to solve the full Navier–Stokes equations owing to its unique advantages of the Lagrangian meshless method, and the non-Newtonian rheology model is incorporated into the governing equations to attempt to represent the debris flow more accurately. Accordingly, the so-called HBP-based SPH model is developed to reconstruct the impact process of the debris flow.

Results: The developed model is firstly verified by the sand flume experiments and then employed to analyze the performance for simulating a real debris-flow event in eastern Italian Alps. The simulated results of the sand flume models provide an accurate prediction of the impact force acting on the rigid wall. A peak impact force is observed in the steeper flume slopes (55°, 60° and 65°), excepting the two flatter flume slopes of 45° and 50° where the impact force appears to increase continuously to a stable impact value. Moreover, two totally different impact mechanisms are observed in the sand flume models of 45° and 65°. The impact mechanism of the 45° inclination flume resembles a granular bore regime while it becomes an airborne jet in the 65° flume. The simulated results of a real debris flow show that the evolution of impact pressure varies with different locations of check dams. The impact pressure in the upper part of the channel appears to be greater than that detected downstream, which can be explained by the steeper terrains and the higher flow velocity upstream compared to downstream. Moreover, combinations of multiple dams appear to gain a better protection effect compared to the single-dam setting. These numerical results contribute to the design and optimization of engineering structures.

Conclusions: Two different impact patterns (granular bore and airborne jet regime) are observed in the sand flume model, which demonstrates that the flume inclination plays an important role in determining the impact mechanisms of debris flows. Analyses of a real debris flow illustrate that obstacles can dramatically diminish the discharge downstream and flow velocity of the flow front. The variation of impact pressure differs at different locations. The detected peak impact pressure generally decreases with the gentler slope of the channel. The prevention effect of multiple dams tends to be better than that of a single dam.

THE ROLE OF FINE CONTENT ON THE DYNAMIC RESPONSE OF SMALL-SCALE SLOPE MODEL

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Purpose: The purpose of the study is to investigate the role of fine content on the behaviour of small-scale slope model subjected to dynamic loading such as earthquake and to examine the role of water content to the overall behaviour. Special focus was given to critical locations of slope such as the crown of a slope and the foot of the slope.

Methods: Pure sand and mixtures of kaolin powder with sand in different mass ratio were used to build a small-scaled slope model. Sand and sand-kaolin mixtures were placed in a rigid model box with adjustable slope inclination. To achieve consistent relative density, undercompaction method was used. All the tests were performed with the slope inclination of 40 degrees. Surface displacements were measured using two high-speed cameras. Accelerometers were placed inside the slope body to measure acceleration response during dynamic loading. The slope models were also instrumented with theta probes and mini tensiometers to monitor the hydraulic response of the slope before and after dynamic loading. Dynamic loading was applied using shaking table. Loading frequency was 5.5 Hz and the amplitude of horizontal displacement was 0.2 cm. Material was saturated before the start of the test.

Results: The acceleration from accelerometers placed inside a slope body were used to calculate the shear stress, the shear strain, degradation of strength and the equivalent viscous damping for the three different soil material. Densification of soil during and after dynamic loading was calculated using the measured accelerations and surface displacement. This provided an insight of post-cyclic compaction. Theta probes and tensiometers showed a change in volumetric water content and matric suction at the end of dynamic loading compared to the values at the start of the test. Measured volumetric water content was grater in the bottom part of a slope model due to dynamic loading.

Conclusions: The performed simulations showed several key aspects. Performed small-scale slope simulations gave interesting results on the dynamic behaviour of slopes that can form shallow landslides. During cyclic loading there is a small densification followed by hardening. No amplification was recorded. The simulations showed that fine content has significant role in dynamic slope behaviour. The slope models on pure sand showed densification prior to the failure. The crown of the slope and the foot of the slope are proven to be the critical parts. Water can infiltrate in cracks on the slope surface and make the slope more saturated which results in softening and additional strength degradation. If the material is highly permeable the water can be accumulated in the lower part of the slope which makes it fully saturated. The research was conducted as a part of a following two projects: “Laboratory Research of Static and Cyclic Behavior at Landslide Activation” (uniri-tehnic-18-113) funded by the University of Rijeka, Croatia; and “Physical Modelling of Landslide Remediation Constructions Behavior under Static and Seismic actions” (ModLandRemSS, IP-2018-01-1503) funded by the Croatian Science Foundation, and presents the possibility of using simple physical models to investigate small-scale slope behaviour.

A THREE-DIMENSIONAL MODEL OF THE GENERATION AND PROPAGATION OF GROUND VIBRATIONS CAUSED BY LARGE-SCALE SEDIMENT MOVEMENT

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Purpose: Deep-seated landslides generate seismic signals that can be used to determine their magnitude and location. Furthermore, they are used to investigate the process of landslide movements. But due to the infrequent occurrence of such phenomena, characteristics of ground vibration incidents generated by landslide movements have not been fully studied. Well-founded numerical approaches for calculating the generation and propagation of ground vibrations would be useful in improving the estimation of landslide properties. It might even be beneficial in the in-depth study of the time-wise process of landslides.

Methods: We developed a numerical model which couples three-dimensional particle flow and the continuum model at the same time. The model can calculate the landslide movement and subsequent propagation of seismic signals over large areas. We applied this model to a deep-seated landslide that occurred in September 2011 in Akadani, Gojo in Japan. We tried to represent the ground vibrations caused by this landslide and compared the waveform of ground vibration which was observed at a seismic station (F-net Nokami) which locates 34.4 km away from the landslide site. We assumed two scenarios for the movements and compared the waveforms derived from the cases.

Results: At a low frequency (0.01-0.1 Hz), the simulation results adequately reproduced the signals observed when the landslide was assumed to be in two blocks in the aspect of both amplitude and phase space (Figure1). In the case of the landslide being in single block, the low frequency component of ground vibration generated by the landslide showed smaller amplitude. The result indicates that the scenario of sediment transport affects the amplitude of ground vibration at low frequency even if the volumes are identical. We also depicted the particle motion of ground in the slope of the landslide. The particle motion during the sediment movement of the simulation results around deep-seated landslide slope is bigger at upper points than lower ones. In particular, the direction of low frequency horizontal displacement during sediment movement in the simulation markedly coincided with the direction at the distant observation point. It may allow us to open up a way to estimate the direction of sediment movement upon further research. On the other hand, a high frequency (>about 1 Hz) signal was not well articulated in this study. The amplitude of high frequency was quite bigger than observed one. It might be caused by the effect of impulsive input of discrete elements or the effect of mesh size of the continuum model. More elaborated approaches for high frequency zones are to be needed in the future.

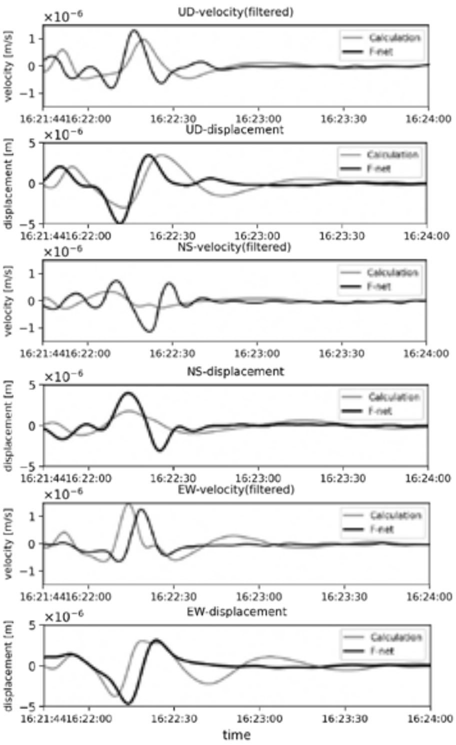

Fig. 1: Calculated and observed velocity, displacement wave form at F-net Nokami. Low frequencies components filtered by 0.01 – 0.1 Hz.
Upper: Up and Down components, Middle: North and South components, Lower: East and West components.

Conclusions: In this study we showed that the numerical model coupling standard methods used in engineering field is capable enough to produce practical estimation of the ground vibrations generated by deep-seated landslides.

A LANDSLIDE PREVENTION PROJECT WITH HIGH CAPACITY SINGLE BORE MULTIPLE ANCHOR IN TURKEY

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Purpose: Permanent anchors in sedimentary rock layers like siltstone, sandstone interbedded with tuff and tuffite layer were proposed to remedy and minimize risk of a potential landslide at a petrochemical facility located in Turkey. In order to strengthen an existing cantilever multi-staged bored piled shoring system with a total shoring height of 35 m; which had been previously constructed by other subcontractor, a landslide prevention project; composed of high-capacity Single Bore Multiple Anchors (SBMA) was designed and proposed. In the stability analysis of the existing shoring system, the location of the sliding surface was determined in advance by field investigations. Upon review of the field investigations, SBMA anchors were positioned and designed outside the possible slip surface, which was determined according to the results of the two-dimensional limit equilibrium and finite element analyzes. A sufficient factor of safety against global stability was achieved under both static and seismic conditions.

Methods: Displacement of the existing multi-row bored piled shoring system were regularly monitored with inclinometer readings. The results of the inclinometer readings were evaluated and an estimated soil model; compatible with the deformations taken from the inclinometers was determined by the back analysis. Two-dimensional finite element and limit equilibrium analyzes were made using this model, and a landslide prevention project was introduced by using SBMA anchors in order to provide adequate safety under both static and seismic loads. A total of 8,950 m of SBMA anchors were executed. Prior to the installation of production anchors, investigation tests were performed with Single Unit Test (SUT) and SBMA type test anchors so as to verify that production anchors would satisfactorily carry 200 tons of static load.

Results: After the installation of SBMA anchors, the deformations of the existing cantilever multi-staged bored piled shoring system; an intensive monitoring program was carried out within the project. Owing to this program, in order to observe long term behavior, vibrating wire type load cells were used for 20 no. of production anchors. Additionally; to monitor lateral displacements and movements of the existing shoring system, inclinometers were installed. These data are very important to observe and investigate actual performance of the shoring system in real time. As a result, lateral displacements and movements of the existing shoring system was stabilized after SBMA anchors were successfully installed. Moreover; a special web-based software was used during testing and anchor installation works. Taking advantage of this software, all drilling, grouting and stressing data of the production SBMA anchors were recorded.

Conclusions: It is concluded that a landslide prevention project consisting of high-capacity pre-stressed SBMA anchors can successfully increase the global safety of the existing cantilever multi-staged bored piled shoring system.

SESSION 2.8

EARTH OBSERVATION DATA FOR LANDSLIDE PREDICTION AND RISK ASSESSMENT

GROUND DEFORMATION DETECTION AND ASSESSMENT OF LANDSLIDE POTENTIAL DAMAGE WITH SUPPORT OF COPERNICUS

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Purpose: The main goal is to utilise Sentinel-1 SAR data, evolving from periodically updated maps of ground deformation to early mapping and monitoring of landslide activity to increase urban resilience. We will provide a prototype service (EO4MASRISK) to increase the capacity of stakeholders involved in risk prevention and preparedness by detecting landslide activity and predicting its potential impact on urban areas and infrastructure. The EO4MASRISK service will help stakeholders and end-users quickly identify landslide-prone areas and their potential impacts on built-up areas.

Methods: In the processing, we used Sentinel-1 images from three orbits (two ascending, one descending, overlapping) from 2017 to 2021. We focused on the period when both Sentinel-1A and B were operational, leading to 6-day time intervals. DInSAR, PSInSAR, and SBAS-InSAR processing were performed for three areas of interest, located in different areas, and displacement time series were generated. Other existing survey data obtained from classical and geodetic GNSS surveys were included for calibration and validation. Several outputs were generated and prepared for mapping and analysis. We also addressed geometric constraints and provided a detailed analysis of the effects of ascending or descending orbit in relation to the orientation of the observed area. Based on field validations and existing data, landslide activity maps were prepared and classified into three risk levels (low, medium, high). By identifying the most vulnerable and exposed elements, we will evaluate potential landslide damage.

Results: The EO4MASRISK service functionality provides the following information: (1) Ground deformation time series; (2) Ground deformation yearly velocity map; (3) Landslide activity map (three levels, e.g., low, medium, high); (4) Map of vulnerable elements at risk, e.g., buildings and infrastructure (three levels, e.g., low, medium, and high); (5) Potential damage map (three levels, e.g., aesthetic, functional, structural).

Conclusions: The EO4MASRISK service is integrated with the Slovenian national landslide prediction system (MASPREM), extending the functionality of the system for early detection of landslides and prediction of potential damage. Therefore, due to the already established communication with the main actor of the MASPREM service, the Administration of the Republic of Slovenia for Civil Protection and Disaster Relief (ACPDR), the developed EO4MASRISK service is immediately used in the operational area and enables appropriate solutions for landslide prevention.

This project EO4MASRISK is funded by the European Space Agency Contract No. 4000139004/22/I-DT-bgh.

COPERNICUS LAND MONITORING SERVICE PRODUCTS IN SUPPORT OF LANDSLIDE RISK MANAGEMENT

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European Environment Agency

The Copernicus Land Monitoring Service (CLMS) is an operational service of the European Union's Copernicus program, which provides accurate and up-to-date information on the state and changes of land cover and land use in Europe and beyond. CLMS utilizes a range of satellite images, in-situ data, and models to provide comprehensive information on land cover, vegetation, water resources, and urban areas, among others.

The CLMS products are designed to support a wide range of applications, including environmental monitoring, land management, agricultural planning, and disaster management. Some of the most notable products include the High-Resolution Layers, which provide detailed and reliable information on e.g., land cover, imperviousness, and forest; the European Ground Motion Service, which delivers ground motion products in 10 billion measurement points; the High-Resolution Snow & Ice Monitoring service, which describes the snow properties on land and ice occurrences on the hydrographic network mostly in near-real time; and the CORINE Land Cover, containing an inventory of land cover in 44 classes.

Overall, the CLMS products are valuable tools for policymakers, researchers, and other stakeholders who need accurate and up-to-date information on land surfaces. They provide an essential foundation for sustainable land management, climate change adaptation, and disaster risk reduction efforts, among other applications. One key characteristic of every CLMS product is the open and free data policy under which they are distributed. CLMS gives users access to reliable and quality-controlled geospatial information that is ready to be used and be integrated into data workflows.

This presentation will give an overview of the product portfolio of CLMS, with a focus on the products of relevance for landslide investigation. Examples of current and potential applications for landslide risk management and mitigation will be provided, while the products' viewing and download capabilities will be highlighted.

IDENTIFICATION OF SLOW-MOVING LANDSLIDES THROUGH AUTOMATED OPTICAL SATELLITE MONITORING OF SURFACE DEFORMATION

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Purpose: Landslides are one of the most damaging disasters and have killed or displaced tens of thousands of people over the 21st century. Slow-moving landslides (i.e., those with surface velocities on the order of 10^{-2}-10^{1} m a^{-1}) can be highly disruptive, but due to their slow displacement and subtle geomorphic signatures, these landslides are often overlooked in local and large-scale hazard inventories.

Methods: Here, we discuss an approach to automatically map slow-moving landslides using feature tracking of freely- and globally-available Sentinel-2 optical satellite imagery. We evaluate this method through three case studies from different environments: the extensively instrumented Slumgullion landslide in the USA, an unstable lateral moraine in Chilean Patagonia, and a high-relief region in Nepal.

Results: Our workflow is able delineate known landslides and identify previously unknown candidate slow-moving landslides in three case studies from very different geographical environments. In a test case on the well-documented Slumgullion earthflow, USA, our workflow effectively delineates the active portion of the earthflow and produced velocity magnitudes consistent with both ground-based instrumentation and previous remote-sensing estimates. In another test case on the margin of the Southern Patagonian Icefield, Chile, we identified a very large (>6 km^2) composite landslide in the eastern lateral moraine of Glacier Occidental – and, conversely, demonstrated that the western flank of this glacier appears to be stable (see Figure). Finally, we identified 20 candidate slow-moving landslides in a 165 km^2 area around the Bhote Koshi valley, Nepal, some of which have previously been mapped and underlie or are in close proximity to densely populated areas.

Conclusions: We evaluate and demonstrate the wide applicability of our proposed workflow through three different case studies. We are able to detect slow-moving landslides in complex environments using 10-m resolution globally available satellite imagery, all without any manual intervention. Taken together, this means that our workflow can be applied to any region on Earth, regardless of the availability or reliability of prior information. Improved mapping of the spatial distribution and surface displacement rates of slow-moving landslides will improve our understanding of their role in the multi-hazard chain and can direct future detailed investigations into their dynamics.

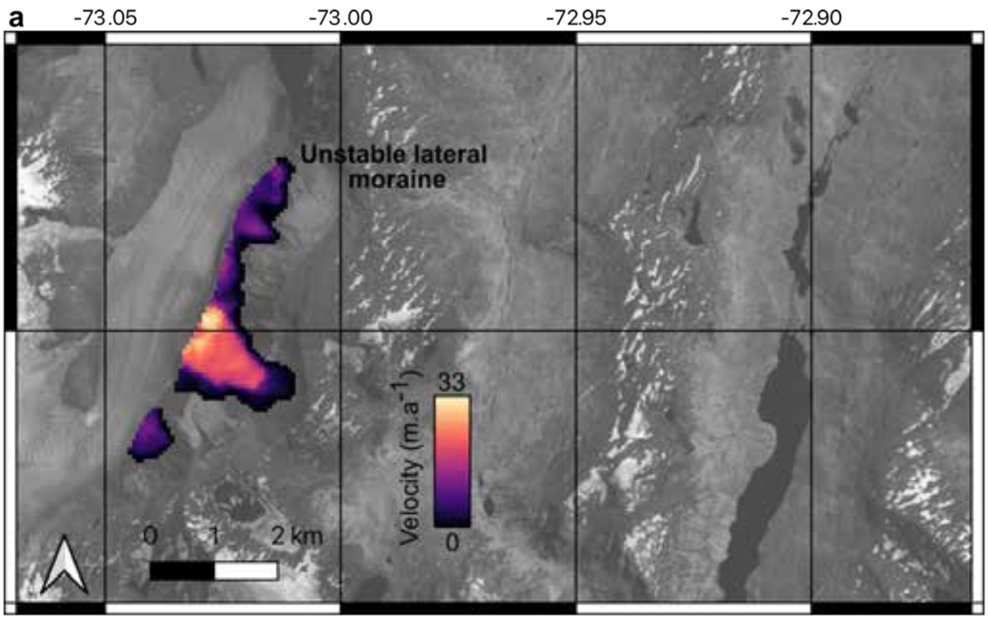

Fig. 1: Large slow-moving landslide complex in the lateral moraine of Glaciar Oriental, Chilean Patagonia detected using our workflow.

INSAR APPLICATION FOR THE DETECTION OF PRECURSORS OF THE ACHOMA LANDSLIDE, PERU

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Purpose: In the last few decades, InSAR has been used to identify ground deformation related to slope instability and to retrieve time series of landslide displacements. In some cases, retrospective retrieval of time series revealed acceleration patterns precursory to failure. Although the higher temporal and spatial resolution of new-generation satellites may offer the opportunity to detect precursory motion with viable lead time, to rely entirely on the possibility of retrieving continuous time series of displacements over landslides is a limiting strategy. This is because successful phase unwrapping is impaired by factors such as unfavourable orientation, landcover and high deformation gradients over relatively small areas, all common on landslides.

Methods: We generated and analysed 112 Sentinel-1 interferograms, covering the period between April 2015 and June 2020, at medium spatial resolution (8 and 2 looks in range and azimuth respectively) over the Achoma landslide in the Colca valley, Peru. This large, deep-seated landslide, covering an area of about 40 hectares, previously unidentified, failed catastrophically on 18th June 2020, damming the Rio Colca and giving origin to a lake. We also generated a time series of displacements based on optical Planet Lab images covering the three years prior to failure. We explored a methodology to retrieve precursory signs of destabilisation of landslides with characteristics unfavourable to unwrapping and time series inversion based on the investigation of spatial and temporal patterns of coherence loss within the landslide and in the surrounding area and on the extraction of a relative measure of incremental displacements through time obtained from the wrapped phase.

Results: We observed significant, local interferometric coherence loss outlining the scarp and the southeastern flank of the landslide, intermittently in the years before failure. Moreover, we observe a sharp decrease in the ratio between the coherence within the landslide and in the surrounding area, roughly six months before the failure which is interpreted as a sign of critical landslide activity and a precursor. The latter is concomitant to increasing displacement rates observed with optical images. The wrapped interferometric phase also revealed a sequence of acceleration phases, each characterised by increasing annual rates. We observe a behaviour that recalls progressive failure, with no clear evidence for response to one particular trigger and two acceleration phases followed by a more stable period and the last leading to failure.

Conclusions: This type of approach is promising with respect to the extraction of relevant information from interferometric data when the generation of accurate and continuous time series of displacements is hindered by the nature of landcover or of the landslide studied, such in the case of the Achoma landslide. The combination of key, relevant parameters and their changes through time obtained with this methodology may prove necessary for the identification of precursors over a wider range of landslides than with InSAR time series generation alone.

CREATION AND UPDATING OF LANDSLIDE INVENTORY INTEGRATING EUROPEAN GROUND MOTION SERVICE AND SURFACE GEOMETRICAL CHARACTERISTICS: THE CASE STUDY OF LOMBARDY REGION, ITALY

Rasoul Eskandari, Alireza Alizadeh Javaheri, Marco Scaioni

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Purpose: Ground instability phenomena and the occurrence of geological events in Lombardy Region (Italy), with landslides being one of the major contributors may lead to significant damages and socio-economic losses (Antonielli et al., 2019). The inventory of landslides of the region provides a detailed picture of the distribution of landslides in Italy for better optimizing mitigation measures and prevention activities. The present work is devoted to analyzing the correlation between surface geometric characteristics and the horizontal/vertical land displacements measured by Sentinel-1 SAR Interferometry provided by European Ground Motion Service (EGMS), seeking the potentiality of landslide inventory creation and update.

Methods: According to literature, the landslide inventory is commonly updated by thresholding the ground deformation rates measured at Permanent Scatterers (PSs) by aiming at detection of possible unstable regions (Guerriero et al., 2019; Infante et al., 2018). Also, several comparative assessments have been performed to temporal evaluation of the landslide movements in different time periods (Confuorto et al., 2023). In this work, DTM Lombardy (Italy) is used to extract the surface geometric parameters, i.e. slope magnitude and orientation ( ). Then, an neighboring window is considered around each EGMS point positioned within the diagnosed landslides in a section of the northern part of Lombardy, to calculate the average of and score of (from 0 to 1) representing the consistency between the orientation of the EGMS point horizontal displacement (easting or westing) and the values of neighboring pixels. Finally, each EGMS point is assigned by a model index: , where the exponents are arbitrary values changing the effect of each parameter.

Results: Figure 1 shows the correlation and the fitted model on and considering all the points within the landslide inventory, using a search window, and . Such a diagram will be developed for different landslide states of activity to be used for creation and updating of the inventory map, since the and defamation velocities are also available for the points outside the training dataset.

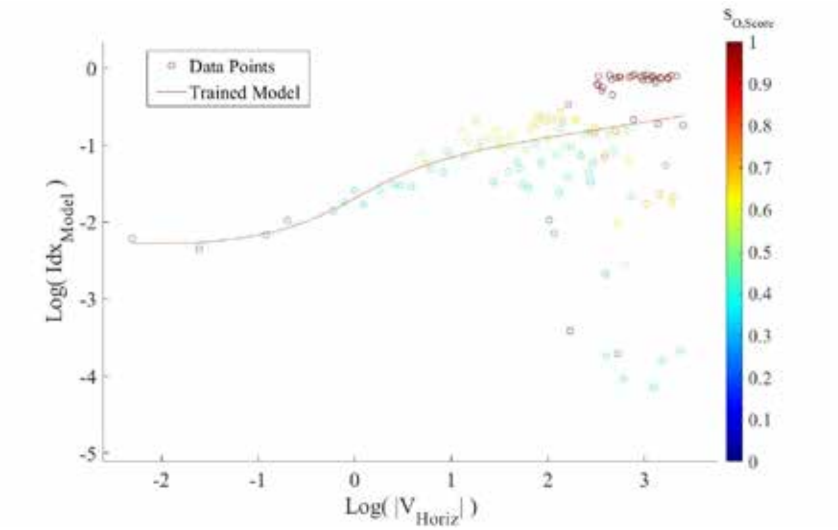

Figure 1

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GIS-BASED LANDSLIDE SUSCEPTIBILITY MAPPING USING LOGISTIC REGRESSION MODEL IN THE GAIZI VALLEY SECTION OF CHINA-PAKISTAN CORRIDOR

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Purpose: As an important pilot project of the Belt and Road Initiative and a new trade network of the inland areas of Western China, China-Pakistan Economic Corridor includes highways, railways, gas and oil and cable channels, benefiting about 200,000,000 people. It is of immeasurable strategic role in promoting regional economic and trade cooperation. It passes through the Kalakoram-Kunlun Mountains, the Himalayas and the Hindu Kush Mountains, as well as the Pamir Plateau. Due to the special geological environment and the climate change, the landslide disasters occurred frequently in the area, which poses a huge threat to engineering construction and operation, and restricts the infrastructure construction, as well as social and economic development along the corridor. The objective of the paper is to obtain the landslide susceptibility mapping for mitigating landslide disasters in the alpine mountainous region of the corridor and propose a method system that can be used in other alpine mountainous regions.

Methods: This paper carried out a landslide susceptibility analysis in the Gaizi valley section of the corridor, using a logistic regression (LR) model with the aid of remote sensing data and GIS tools. The landslide inventory map was prepared according to historical data and interpretation of high resolution satellite images (GF-2 0.8 m resolution), and verified by field investigations. An inventory map with 33 landslides locations was obtained from many sources. Due to the study region is the alpine mountain area, the temperature and permafrost distribution were selected as the conditional factors, besides the normalized difference vegetation index (NDVI), slope, slope aspect, curvature, elevation, drainage network, road, rainfall, lithological unit and lineament. The final causative factors was determined by a frequency ratio (FR) model.

Results: The landslide susceptibility map was obtained using LR on the basis of landslide inventories and causative factors. For verification, receiver operating characteristic curves were calculated and the area under the curve (AUC) for prediction is 0.71 for the LR. In addition, the percentage of existing landslides data in high and very high zones of the susceptibility map is of 73.2 for the LR. The value of AUC is above 0.7 which indicate the LR is suitable for susceptibility analysis for this region. Also, percent of landslides data of high and very high zones indicate that LR model is accurate. The results showed that the landslides occurred in many places in the Gaizi valley section of China-Pakistan Economic Corridor, and mainly distributed on the slopes on both sides of the China-Pakistan road and on the glacial front area northern to the Bulunkou.

Conclusions: The paper obtained the susceptibility map of landslides in the alpine mountain area and benefit for its future applications to the China-Pakistan Corridor. The regional landslide susceptibility results are of great significance to the construction and the protection of basic engineering facilities, and the sustainable economic and social development of the China-Pakistan Corridor.

SESSION 2.2

INTEGRATED APPLICATION OF DEFORMATION MONITORING TECHNIQUES AND PROCESS ANALYSES OF DEEP-SEATED LANDSLIDES (part II)

UNDERSTANDING THE LANDSLIDE DYNAMICS WITH CORNER REFLECTOR SAR INTERFEROMETRY

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Purpose: The main factor that is triggering landslides in Carpathians is rapid groundwater level change after heavy and long lasting precipitation periods. Depending on local geological structure and slope characteristic the sliding process might have different way of development over the time. In order to investigate to what extent even minor changes in the hydrological and hydrogeological environment affect the changes in the dynamics of the displacement various types of measurements are used. The volume of precipitation is recorded by rain gauges installed in the close proximity of studied landslide and groundwater level variations are recorded by limnimeters in piezometric boreholes. Surface displacements are measured with laser scanning and on dedicated benchmarks with GNSS (Global Navigation Satellite Systems) instruments whereas underground deformations are recorded in inclinometer boreholes with inclinometric probe. Despite of its cost and effort effectiveness, the major disadvantage of this commonly used monitoring system is huge discrepancy between hydrogeological data (semi – continuous, recorded automatically with hourly rate) and deformation measurements which are taken twice per year. Therefore, based on such data the only very broad conclusions can be taken.

Methods: In order to improve a temporal sampling of surface deformation record a set of radar corner reflectors (CR) for SAR (synthetic Aperture Radar) interferometric measurements has been deployed on 5 selected already monitored landslides in Carpathians in Poland almost 5 year ago. Special construction of corner reflectors allowed for ascending and descending Sentinel1 observations and also GNSS measurements for validation purposes. Each from selected locations was equipped with 6 CR. Careful processing and decomposition from Line of Sight to Up and East of combined data from all available tracks and Sentinel-1 A and B satellites allow to reconstruct daily record of CR displacements. CR displacement data from locations of closest piezometer borehole were analyzed together with hydrogeological data.

Results: In author's opinion such combination permit for the first time to draw proper and reliable conclusions. The delay between precipitation event and landslide movement acceleration can be studied in details on the background of seasonal effects. Also dependence on geological structure and lithological composition of different landslides is clearly visible and can be studied in details.

Conclusions: Corner reflectors become an important tool for scientific monitoring allowing to study landslide movement in great detail and also support creation of the models of landslide dynamics and precipitation thresholds.

6th WORLD LANDSLIDE FORUM
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LANDSLIDES VS LAND SUBSIDENCE AT THE PERIMETER OF OPEN PIT COAL MINES. THE CASE OF THE ANYNTAIO COAL MINE, GREECE

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Purpose: Land subsidence, affecting the plain area surrounding the open pit mines, as well as extensive landslides, affecting the open cast slopes, are listed among the most intensive mining induced catastrophic geo-hazards taking place the perimeter of the mines. These large-scale geohazards are related both to hydrogeological and geotechnical parameters and they cause unrevoked damages. The present study investigates the area extending at the perimeter of the Amyntaio opencast coal mine at Florina Prefecture, Northern Greece. The overexploitation of the aquifers for the dewatering of the slopes turned the mine to a large diameter well triggering land subsidence since 2005 [1]. The surface deformations caused by the subsidence extend 1-3km around the mine affecting several urban sites. Above that, on June 10, 2017, a massive landslide, of approximately 80 million cubic meters, occurred at the working slopes of the mine, burring 25 million tons of lignite, resulting in severe damage to large number of mining equipment and causing the evacuation of the nearby Anargyroi village (Figure 1). The current study investigates land subsidence and landslides, highlighting the influence and the interaction of their triggering factors.

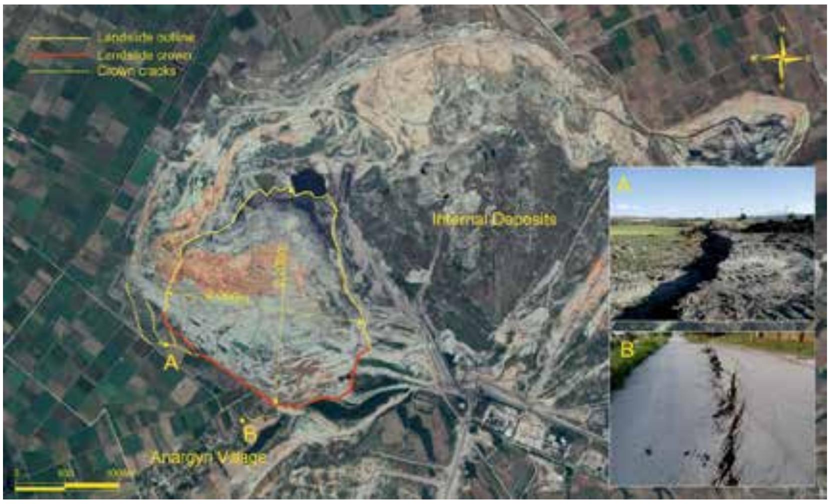

Fig. 1: The June 10, 2017 massive slope failure at the Amyntaio open pit coal mine.

Methods: To estimate ground surface movement, Earth Observation data from the European Ground Motion Service, of the Copernicus European Union's Earth observation program, were used for the period 1 January 2016 – 31 December 2020. The geologic, geotechnic and hydrogeologic data [2] coming from the extensive ground truth survey have been incorporated with the Earth Observation data highlighting the opposing mechanisms of the interacting geohazards [3].

Results: Evaluating the driving mechanisms, it is clear that the occurring catastrophic events were driven by contradictive casual factors. The dewatering of the slopes triggers the land subsidence while the attenuation of the draining reduces the safety factor of the slopes.

Conclusions: The current research, besides presenting the two catastrophic events, correlate the geological, hydrogeological, and geotechnical factors affecting both phenomena, outlining their opposing mechanisms. The study proves the necessity of the establishment of a holistic development plan supported by focused geotechnical and hydrogeological studies. This way, the occurrence and the diametric drivers of both types of catastrophic events can be evaluated and predicted, minimizing their effects on the mining activities and the surrounding environment.

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THE IMPORTANCE OF SUBOSOIL MEASUREMENTS TO THE DEEP-SEATED GROUND DEFORMATIONS INTERPRETATION. THE ESPERIENCE WITH A ROBOTIZED INCLINOMETER SYSTEM ON 240-METER TUBE LENGTH

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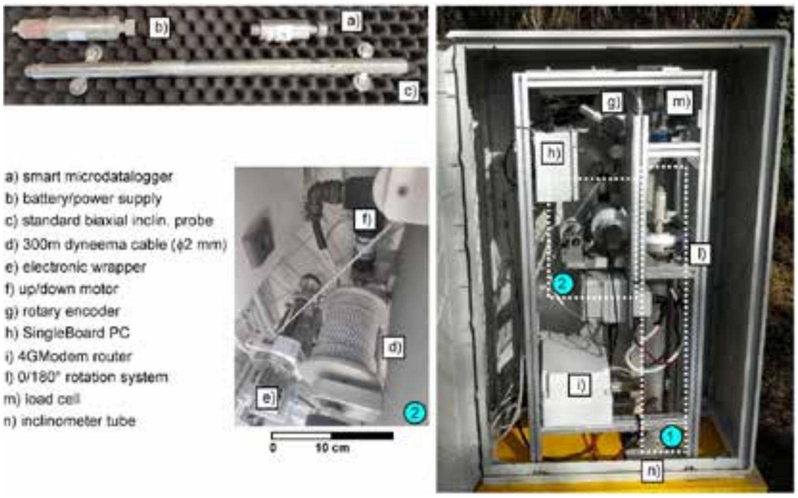
Purpose: Deep seated ground deformations with slow kinematic represent a widespread phenomenon in several mountainous area. These phenomena often interact with strategic infrastructures (e.g., dams, motorways, railway lines, penstock) and can represent a critical issue for the structural life. The remote sensing techniques allows in some cases to follow the surface deformation evolution, but not the subsoil deformations. This limitation can create critical issues in the interpretation of the type of phenomenon (or phenomena), its state of activity and the real volumes of the active landslide. Frequently these unstable areas are characterized by overlapping phenomena featuring different kinematics, evolution and materials that cannot be identified using only surface deformations data (by remote sensing, GNSS).

Methods: To reduce the interpretation uncertainties, it is increasingly necessary to monitor ground deformations even at great depths in order to fully describe the space/time evolution of a meaningful site of the observed phenomenon. These observations are normally carried out using manual inclinometric measurements or sometimes automatically with in-place inclinometers (IPI). For both solutions, criticalities are frequently highlighted in the case of very long inclinometer tubes (> 120÷150 m depth) both for the execution of manual measurements (weight of the equipment, measurement difficulty, accessibility of the sites) and for the costs of IPI (direct proportional to the tube length). We present an innovative version of the robotic inclinometer system (long-range version) that has been developed; this instrument can explore and measure vertical inclinometer tubes up to 250 m long. This system, already widely used in Italy and Europe, allows automatic inclinometric measurements using a single probe in a robotic way, with a vertical discretization of 50 cm (Allasia et Al, 2020). The instrument carries out the measurement automatically following the principle of traditional inclinometric one with 50 cm steps, double measurement (0/180°) and biaxial type probe, independently of the length of the tube.

Results: The preliminary result confirms the high quality of the acquired data also considering the very long tube and the measurement timespan (about 6 hours). The system has been confirmed also extremely versatile in terms of measurement scheduling (up to 2 per day for 240 tube lengths)

Conclusions: The new long-range version is currently being used for a preliminary survey in the design of deep-seated railway tunnels, representing a useful and innovative instrument for surveillance along sensitive sections of infrastructure facilities for a better risk assessment and mitigation strategies implementation.



Main components of Robotized Inclinometer System (XL Version up to 250 meters tube length)

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INTERNAL DEFORMATION OF AN ACTIVE, DEEP-SEATED, MULTI-SLAB ROCK SLIDE AND ITS CONTROL ON SECONDARY ROCK FALL PROCESSES - CASE AND NUMERICAL MODELLING STUDY OF THE WASSERRADKOPF ROCK SLIDE

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Purpose: We present a case study focusing on the active, deep-seated, multi-slab rock slide on the south-eastern slope of the Wasserradkopf (3032 m a.s.l.) located in the 'Hohe Tauern National Park' (Austria). The rock slide incorporates an area of 1.5 km2 and is composed of highly schistose and heavily foliated rocks allocated to the 'Bündnerschiefer' of the central Tauern Window. From its disintegrated rock slide mass, secondary rock fall processes occurred. We investigate the complex structure of the rock slide system and demonstrate the impact of its internal deformation on secondary rock fall processes.

Methods: For this purpose, we performed a geological field survey, characterizing the lithologies and structural inventory of the rock mass composing the Wasserradkopf. Additionally, we mapped distinctive geomorphological phenomena in the field, which are inherent to deep-seated rock slides, e.g. main, minor, and uphill-facing scarps. This theme-based mapping enabled us to identify the spatial extent of the rock slide, as well as to infer its thickness and the presence of individual rock slide slabs. Analysis of satellite-borne interferometric synthetic aperture radar (InSAR) data at high temporal and spatial resolution provided the determination of active areas of the rock slide. Pre-existing results derived from two different InSAR algorithm methods (SqueeSAR and FASTVEL) showed differential movement rates on the rock slide, thereby confirming the previously mapped individual rock slide slabs. Based on the field survey and deformation analysis by InSAR, we developed a geological-kinematical model. We then implemented the mapped structural inventory and the reconstructed pre-failure topography into a 2D distinct element model (UDEC) to investigate the deformation characteristics of the rock slide. Thereby, we studied, whether the mapped geomorphological surface features, individual slabs with differential movement rates, and secondary rock fall processes can be reproduced by the geomechanical model.

Results: This integrated approach of InSAR techniques and geological-geomorphological field studies enabled us to identify at least three main rock slide slabs. Preliminary results from our distinct element model suggest that disintegration of the rock slide in individual slabs and the location and type of the mapped geomorphological features are favoured by the pre-existing, structural inventory. A remarkable observation is, that a higher-up located rock slide slab, which was formed by a retrogressive failure mechanism, shows higher movement rates than the adjoining, lower slab.

Conclusions: These different movement rates lead to bulging at the foot of the upper slab, due to de-buttressing effects caused by the original displacement of the lower slab. This causes intensive rock mass fracturing and fragmentation into blocks which in turn leads to increased rock fall activity in the area, endangering a busy tourist road below. Understanding of the process underlying the rock fall activity is key in performing a comprehensive hazard assessment for this high value infrastructure.

REACTIVATION OF A DEEP CLAY LANDSLIDE INDUCED BY EXCEPTIONAL RAINFALL EVENTS: A CASE STUDY

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Reactivation of deep clay landslides along pre-existing shear bands is frequently associated to the cumulated effect of rainfall events over long periods. However, in some cases, abrupt and rapid reactivations of earth-slides can develop after single exceptional meteoric events. In December 2013, a portion of a large and deep ancient landslide was reactivated close to the Montescaglioso urban area (Basilicata, Southern Italy), after 52-hour high-intensity rainfalls, causing large shear displacements, with damages to the overlying buildings and roads. Based on the available field measurements and the geomorphological evidences, the sliding surface has been recognized at depths ranging between 10 and 50 m from g.l., within a thick deposit of Pleistocene stiff clays, overlain by dislocated blocks of cemented conglomerates. This contribution is aimed at presenting the research activity that has been carried out to recontruct the landslide mechanism and the factors that controlled the slope reactivation.

The study has been developed by means of a detailed geomorphological analysis, the interpretation of the available database of the geotechnical properties of the involved soils, a two-dimensional seepage finite element analysis to reconstruct the transient flow process during the rainfall event, a limit equilibrium analysis as well as a three-dimensional finite element analysis of the overall slope failure mechanism.

In particular, geological and geomorphological analyses performed via field surveys and remote sensing analyses as well as inclinometer measurements allowed to infer the geometrical features of the landslide mass. The seepage analysis results suggested that water infiltration down to large depths, and the consequent increase of pore water pressures, can be explained only invoking large mass permeability values of the clay formation. The limit equilibrium analysis instead confirm that the mobilized strength of the soil is close to the residual value and provide indications on the variation of the slope safety factor during the rainfall event, up to the landslide triggering. The three-dimensional finite element analysis allowed to derive an insight into the overall landslide displacement field, in terms of extent of the unstable area, soil failure evolution within the slope and, also, allowed to have insights into the main landslide movement directivity, in accordance with the in-situ landslide mobility, as reconstructed from geomorphological mapping, DTM surveys and satellite interferometry analyses.

Based on the results of the analyses carried out, the main factor responsible for the landslide reactivation is recognized in the rapid increase of pore water pressures within the landslide mass, even at large depths, which should depend on the large field permeability values of the clay mass and the aperture of vertical fractures in the slide area, although other factors could have potentially contributed, as the breaking of a pipeline within the slide area.

SHEAR DISPLACEMENT CALCULATION OF LANDSLIDE BASED ON DISTRIBUTED STRAIN SENSING TECHNOLOGY

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Purpose: In recent years, Distributed Fiber Optic Sensing (DFOS) has become an emerging technology for automatic landslide monitoring due to its unique advantages over traditional methods. It is noted that the Distributed Strain Sensing (DSS) cable can merely measure the axial strains along the total length, and how to convert strain into shear displacement remains to be explored.

In this study, an Accumulative Integral Method (AIM) for determining the shear deformation of landslides is proposed and its validity is subsequently verified against laboratory shear test results.

Method: A novel shear displacement calculation method is developed herein, as illustrated in Figure 1. a_i (i = 1, 2, 3…n) denotes the measurement points. ε_i and D_i (i = 1, 2, 3…n) are the corresponding strain values and transverse displacements of each measurement point, respectively. The longitudinal and transverse distances between adjacent points are l_0 and d_i, respectively, as illustrated in Figure 1b. Based on the Pythagorean theorem, the transverse displacement between adjacent measuring points can be calculated:

$$(1)\ d_i=\sqrt{(l_0+l_0\cdot\varepsilon_i)^2-l_0^2}$$

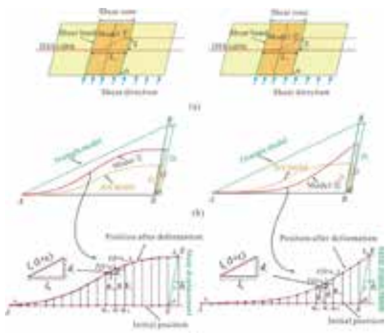

Fig. 1a: Different deformation patterns of the DSS cable; b. Shear displacement calculated using AIM.

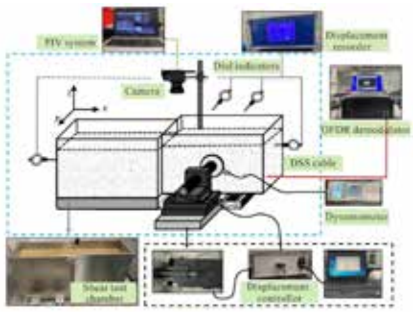

Fig. 2: Shear model test.

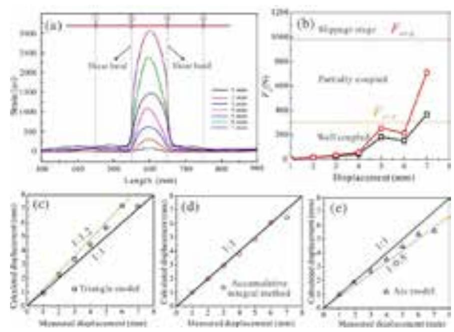

Fig. 3: a. Strain variation along the DSS cables and b. Force acting on the anchors versus displacement. Calculated displacement using the triangle model c., AIM d., and arc model e. versus measured displacement.

Then, the transverse displacement can be derived by summing all the transverse displacements between two adjacent measuring points:

$$(2)\ D_n=\sum_{i=1}^{n} d_i$$

Consequently, after determining the shear angle α, the shear displacement S can be derived:

$$(3)\ S=D_n/\sin\alpha$$

Results: To verify the proposed method, a laboratory shear test was conducted. As shown in Figure 2, the left part of the shear box remained fixed and the right part is applied with a stepwise shear displacement. The displacements derived based on the triangle model, AIM, and arc model are plotted with respect to the displacement recorded by dial indicators, as shown in Figures 3c, 3d, and 3e. It is observed that the shear displacement derived based on the proposed method is more accurate than the triangle and arc models, with a relative error of 6.5%, providing evidence for its feasibility and superiority in the calculation of shear displacement.

Conclusion: To calculate the shear displacement of a landslide while utilizing DSS technology, a novel general landslide shear displacement calculation method is proposed without assuming the shape of the DSS cable. The performance of the proposed method is verified and the proposed method demonstrated a relative error of approximately 6.5% in laboratory tests, outperforming triangle and arc models.

SESSION 4.10

LANDSLIDE RISK MANAGEMENT: THE CHALLENGES OF TRANSDISCIPLINARY RESEARCH IN DATA-SCARCE ENVIRONMENTS

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A REVIEW OF LANDSLIDE AND CUT SLOPE GUIDELINES

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Purpose: Multiple guidelines exist world-wide for landslide assessment and cut slope design. These vary in scale of application (i.e., regional, national, or international), purpose (e.g., preparedness, response, and/or mitigation), target audience (e.g., engineers, decision makers, and/or researchers), focus (e.g., landslides and/or cut slope) and author type (government departments, international donor organizations, research institutions, or engineering companies). They also vary in rigor and usability. We aim to review such guidelines to identify trends and differences in what is presented as best practice and identify improvements that can be drawn from the transdisciplinary landslide community. This review is of particular importance to inform the future development of guidelines for practitioners in data-poor regions (e.g., low and lower-middle income countries) that rely heavily on guidelines for decision making, as they do not have rich historic datasets and data acquisition for every individual slope is too costly (Robson et al. 2022). Here, we discuss the methodology for compiling the guidelines for this review.

Methods: We have compiled landslide and cut slope guidelines from various geographical regions across the world that capture the diversity of guidelines discussed. Guidelines were compiled by conducting keyword searches on online research databases and internet search engines, as well as by requesting copies of guidelines from colleagues situated in different regions of the world, including colleagues from the South East Asia Landslide (SEAL) Network. The guidelines were compiled in NVivo software, where common themes were identified and categorized by using the in-built coding system.

Results: In total, we compiled 14 landslide guidelines and 19 cut slope guidelines. All the landslide guidelines and 15 of the cut slope guidelines are national/regional guidelines (by government departments or research institutions), whilst 4 are international guidelines (by research institutions or international donor organizations). The regional/national guidelines are sourced from 15 different countries (see Figure 1). This review is biased towards guidelines that are open-source and available digitally.

Fig. 1: World map highlighting the country of origin of regional/national guidelines included in review.

The review is divided into five key categories which are further subdivided based on themes identified using NVivo. The key categories are: (1) risk analysis (subcategories of inventory mapping, vulnerability mapping, susceptibility mapping, hazard mapping, risk mapping, and land use planning); (2) response (subcategories of monitoring, emergency response, remediation, temporary works, and education); (3) investigation and analysis (subcategories of ground investigation, geomaterial characterization, and stability analysis); and (4) mitigation (cut/fill slope, erosion control, rock slope stability, soil slope stability, maintenance, quality assurance, aesthetic considerations, and environmental considerations).

Conclusions: This research compiles a diverse set of landslide and cut slope guidelines that are reviewed according to key themes. This review will inform the development of future guidelines on best practice of all aspects of landslide and slope management, which will be of particular importance to data-poor regions that rely heavily on such guidelines.

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THE URGENT NEED TO PROTECT THE WORLD'S POOR FROM LANDSLIDES

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Purpose: As cities expand, more people live on steep hills prone to landslides during rainfall. Population and urban expansions are most rapid in tropical low- and lower-middle-income countries. In 2020, 9.4 million people lived on hillslopes steeper than 20° compared with 1.2 million in 1990. By 2050 this number will likely exceed 13 million. Climate change impacts are also expected to be severe in humid regions, such as the tropics, by doubling the frequency of landslide relevant rainfall events. The likelihood and consequence of landslides is most severe in informal settlements; (i) where unregulated construction practices such as deforestation, slope cutting and terracing, and poor drainage often reduce slope stability; (ii) while the physical, social, and economic conditions increase these communities' vulnerability. These tropical countries typically lack landslide risk mitigation capacity to tackle landslide causes and impacts. Yet, the quantification of these rising risks in tropical countries is poorly quantified.

Methods: We demonstrate how mechanistic modelling aids in exploring the dynamic natural-human landslide risk interactions.

Results: We provide evidence of rising risks for informal settlements in the tropics. The results show that informal urbanization could increases landslide hazards up to fivefold, and warming climate-driven intense rainfall exacerbates landslide triggering conditions further.

Conclusions: Combining global projections of urbanization and climate with mechanistic models enables analyzing the drivers of landslide hazards in unprecedented ways, thus providing valuable information for international policies and community-targeted actions for pro-poor landslide risk reduction.

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6th WORLD LANDSLIDE FORUM
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LANDSLIDE SUSCEPTIBILITY ASSESSMENT OF VERY WIDE AREAS: THE CASE OF CENTRAL ASIA

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Purpose: Central Asia, comprising the territories of Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan, is a very large area characterized by a high variability from a geological, geomorphological, and climatic point of view. Furthermore, complex tectonics and active seismicity (especially in the mountainous areas) are often responsible of large earthquakes, which together with rainfall can trigger several types of landslide phenomena (mainly very large rockslides and earth-debris slides-flows). In this context infrastructures, settlings, agricultural/pasture lands, and human life are exposed to a high landslide risk.

Methods: in the framework of the SFRARR Project ("Strengthening Financial Resilience and Accelerating Risk Reduction in Central Asia") the first comprehensive landslide susceptibility analysis at a regional scale for Central Asia was developed. To this aim several landslide inventories, covering both national and transboundary territories were implemented in a Random Forest model, together with several independent variables. Among these latter, while seismic data (PGA, active faults, and earthquake databases) were accurate, updated, and widespread, there was a complete lack of national topographic, land use, lithology, and rainfall data; therefore, it was necessary to rely on the available global data (e.g., Merit, Copernicus, USGS, ERA5 and OpenStreetMap databases). Furthermore, most of the landslide inventories were partially complete (often no information on the type of movement or triggering date were provided), not harmonized (some inventories were made of points, other by polygons), and not widespread: regarding the two largest countries of Central Asia, no data were provided from Turkmenistan, while for Kazakhstan only a small inventory covering the southern mountainous area north of the Kyrgyz Republic was available.

Results: This work was designated to create a comprehensive, homogenized, high-resolution landslide susceptibility map of the whole study area, avoiding boundary effects. This approach required the setup of procedures and approaches capable of managing a high volume of data with different nature, values, and origin.

Conclusions: The results represent an innovation in terms of resolution (from 30 to 70 m) and extension with respect to previous landslide susceptibility and hazard zonation models applied at a regional scale in Central Asia. The final aim was to provide a useful tool for land use-planning and risk reduction strategies to landslide scientists, practitioners, stakeholders, and decision-makers.

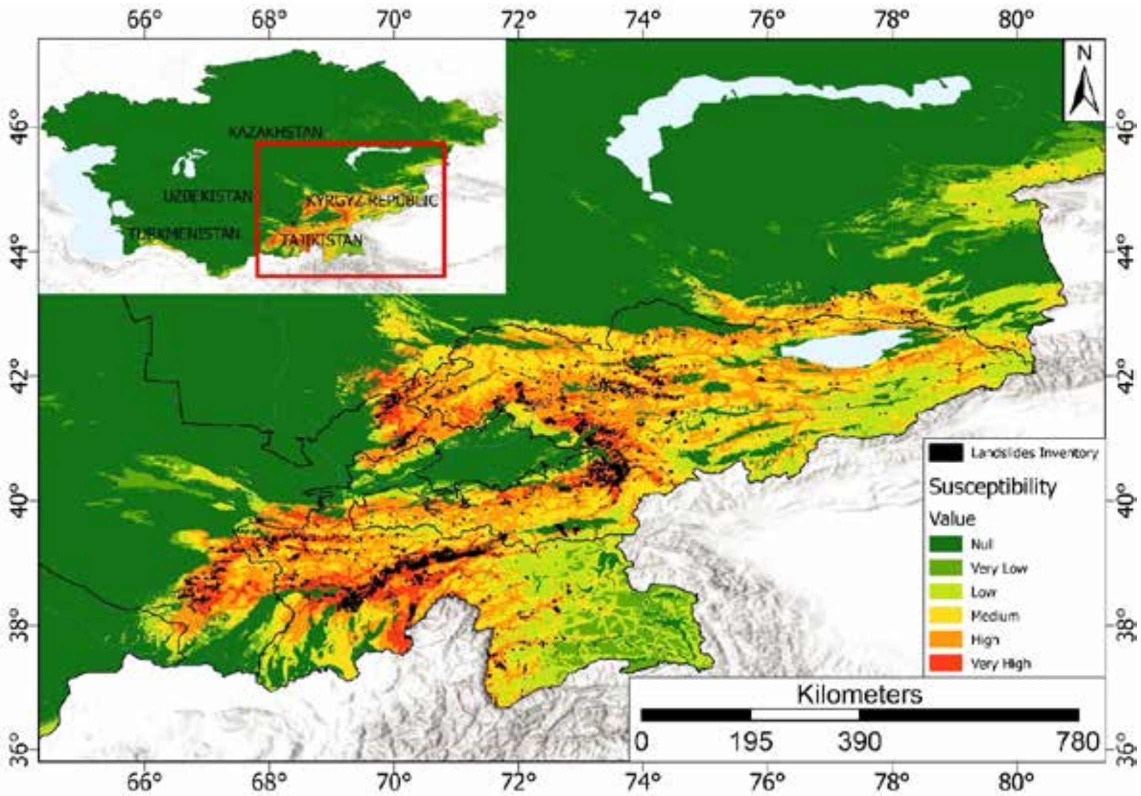

Fig. 1: Detail of the landslide susceptibility map with the overlapping landslide polygons (in black). On the top left the detailed area with respect to the central Asian territory. Basemap source: Esri, USGS, NOAA.

HARMONIZED METHODOLOGY FOR CROSS-BORDER HAZARD AND RISK ASSESSMENT OF EARTHQUAKE-INDUCED LANDSLIDES AT REGIONAL SCALE

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Purpose: This paper presents harmonized framework for earthquake - induced landslide hazard and risk assessment at regional scale. The presented framework is consisted of several steps for landslide hazard and risk assessment applied to the cross-border region between North Macedonia, Albania, and Greece.

Methods: The European ELsusv2 initiative is selected as a harmonized approach for regional landslide susceptibility mapping for the area study. An analytical relationship is used to assess the permanent slope displacement at the surface, for different earthquake scenarios involving the soil type based on Eurocode 8. The final product of the landslide hazard zonation is presented by digital maps showing the expected permanent ground deformation PGD for pre-defined earthquake scenarios, [1]. Harmonized regional risk exposure model for the basic services - schools and hospitals of the cross-border region (CBR) has been developed in GIS (Geographic information System) environment including their structural characteristics (construction material, number of floors, age etc.) as well as their urban function. The damage to bridges due to earthquake-induced landslides was estimated, since bridges are among the main components of the transport infrastructure. Such estimation has required a basic knowledge of the bridges in the CBR (e.g., static scheme, construction material, number of spans, etc.), on the basis of which they were then classified into taxonomies, as well as the hazards to which they are exposed (e.g., PGD) Existing empirical fragility curves are then utilized for a selected number of bridges, chosen according to their position and importance in terms of cross-border connection.

Results: The level of earthquake-induced landslide risk was defined for the regional risk exposure model consisted of schools, hospitals and bridges. Obtained data have been included in a web based platform designed to collect, organize and visualize the project target area including the landslide risk scenarios related to the considered exposure dataset.

Conclusions: The presented framework for the cross-border territory is tool used to identify the hazardous areas and quantify risk of basic services and transport infrastructure, where only limited geomorphological, geological and seismological datasets along with exposure database exist at regional scale. The presented research was performed in the framework of the project named CRISIS ("Comprehensive RISk assessment of basic services and transport InfraStructure") supported by the Union Civil Protection Mechanism, [2], [3] and can be applied to other transboundary regions. The performed earthquake-induced landslide risk assessment will contribute towards improved long-term risk mitigation strategies in each of the countries involved in the study.

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2. D 2.3 Landslide hazard cross-border harmonization and mapping, CRISIS, 101004830, UPCM-2020-PP-AG.
3. D4.2 Cross Border Risk Assessment of Basic Services and Transport Infrastructure, Vulnerability assessment based on seismic and landslide hazard, CRISIS, 101004830, UPCM-2020-PP-AG.

Keywords landslide hazard, landslide risk, earthquake, permanent ground displacements, cross-border region, civil protection.

TORRENTIAL COUNTER MEASURES IN THE KRVAVEC SKI AREA AGAINST DEBRIS FLOODS

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Purpose: During an extreme May 2018rainfall event a debris flood occurred in the torrential area upstream the bottom station of the Krvavec ski resort cabin lift (Bezak et al., 2020). The return period of the event was estimated to be higher than 50 years. More than 20,000 m3 debris was transported in two torrents, and more than 10,000 m3 were deposited near the cabin lift. After the preliminary investigations and design of the mitigation measures (Bezak et al., 2020), until now several torrential protection measures were executed in the field to reduce future risk (Sodnik and Mikoš, 2022). The applied measures can be mostly classified as classical engineering structural (grey) measures without much green elements. This contribution reviews the applied mitigation measures and briefly presents hydro-meteorological and geodetic monitoring that will be used to observe and monitor future extreme events.

Methods: After the May 2018 extreme event several investigations (e.g., geological, hydrological and debris flow modelling, etc.), were conducted in order to prepare the required data for the design of specific structural mitigation measures (Bezak et al., 2020; Sodnik and Mikoš, 2022). The idea was to reduce the risk of several torrential hazards (i.e., flash floods, debris flows, debris floods).

Results: The proposed mitigation measures include restoration of the torrential stream upstream from the cabin lift, a large open-slit check dam with capacity of 14.000 m3 at the confluence of the two upstream torrents, several smaller concrete check dams in their channels, and a series of flexible net barriers to reduce erosion process intensity and prevent future debris flows (Figure 1). Most of the planned protection measures have been already constructed and detailed monitoring system has been established in order to measure and observe potential debris flows and debris flood events. The measuring system includes, for example, Geobrugg GUARD to observe corrosion of nets, a video monitoring system and geodetic field surveys are being conducted periodically using small drones (UAV). Additionally, concrete mixture abrasion monitoring has been established, observing different types of concrete mixtures.

Conclusions: This contribution reviews torrential countermeasures in a Alpine area in Slovenia and describes the local monitoring system.

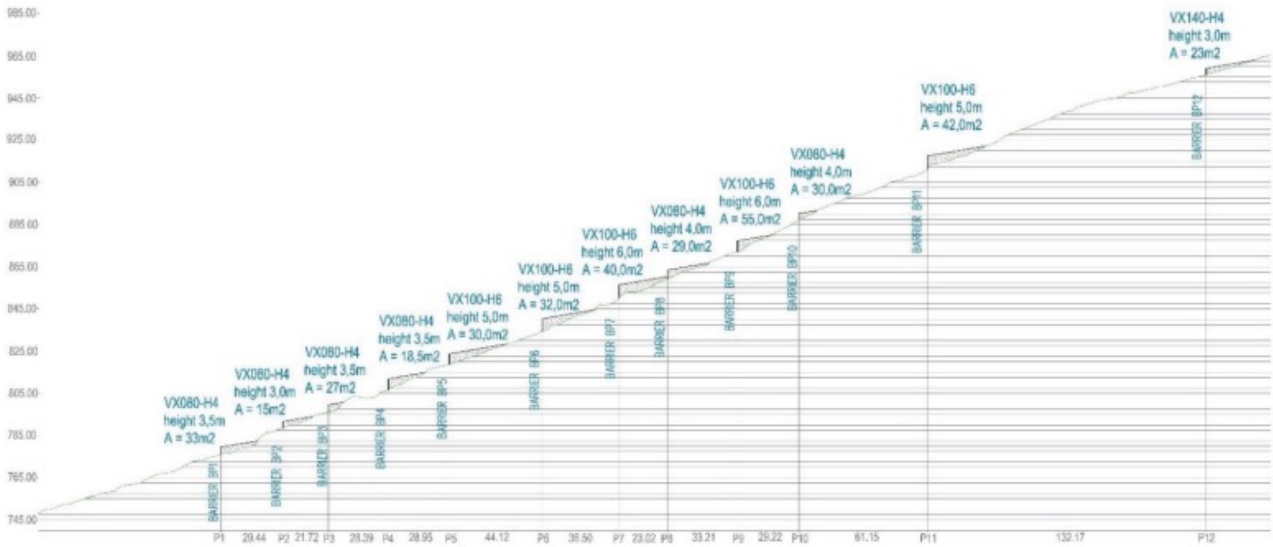

Fig. 1: A longitudinal profile of one of the torrents with the locations of the twelve flexible net barriers that were constructed. The main aim of the flexible net barriers is to prevent side erosion (bank collapses, slumps) and thus to limit sediment supply from sediment sources.

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Acknowledgments: The results of this study are part of the research project and program funded by the ARRS (J6-4628 and P2-0180). The design and of mitigation measures was financed by the Slovenian Water Agency.

RECONSTRUCTING THE SURFACE MOVEMENTS OF THE CAROBBIO LANDSLIDE AT TWO SITES ALONG THE PARMA TORRENT AT THE MULTI-DECADAL SCALE

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Purpose: Slope failure along the Parma Torrent are recurrent landslides that result from the interaction of river dynamics, mainly removing material from the slope toes, and gravitational slope processes. To better understand the events occurring along the torrent and their frequencies through time, a time perspective is mandatory, and multi-decadal reconstruction of landslide surface movements can be performed on forested slopes, by means of tree-ring techniques.

Methods: The integrated use of dendrogeomorphological and GIS techniques has led to successful reconstructions of landslide surface movements at the multi-decadal scale in the Italian Alps (Gattinoni et al., 2019; Leonelli et al., 2020). The same approach based on the analysis of the tree-ring eccentricity, was applied also at the Carobbio landslide, a complex (roto-translational) slide involving marly-limestone flysch formation, at two sites along the Parma Torrent, right river bank. At one site a landslide event occurred, likely in 2010-2011, causing the displacement of 17-20 m of an area of approximately 36’000 m2; a second site was selected south of to the first one, on a slope not yet interested by landslide events in the recent years.

Results: At the northern site, we could date slope movements up to the 1960s, however major signals where recorded since 1971 and 1972 in the higher portion of the slope (with eccentricity values at approximately 20%), whereas in the lower portion of the slope the major signal were recorded only since 1997 (with eccentricity values between 20 and 25%). At the southern site although no events occurred in the recent past, most of trees present decreasing eccentricity values (up to 20% in recent decades) indicating an ongoing recovery since higher disturbances recorded in the 1970s. Here, however, a group of trees shows an increasing trend of eccentricity, with values as high as 30% already in the 1970s and up to 40-50% in recent decades.

Conclusions: The integrated use of dendrogeomorphological techniques on forested slopes along the Parma Torrent together with GIS techniques has allowed the reconstruction of landslide surface movements at the multi-decadal scale at two sites. As we found, disturbance signals have been recorded by trees on the slope already since 40 years (upper portion) and 15 years (lower portion) before the major event observed at the northern site. The slope at the southern site is mostly in equilibrium conditions, although it presents an area in the SE portion that is recording strong signals of surface movements, indicating an ongoing gravitational stress.

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LANDSLIDE HYDRO-METEOROLOGICAL THRESHOLDS IN DATA SCARCE AREAS OF RWANDA

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Purpose: For the development of regional landslide early warning systems, empirical-statistical thresholds are of crucial importance. The thresholds indicate the meteorological and hydrological conditions initiating landslides and are an affordable approach towards reducing people's vulnerability to landslide hazards. This research explored defined different landslide hydro-meteorological thresholds in Rwanda and evaluated their predictive capabilities.

Methods: We identified the key hydro-geological and meteorological parameters in landslide-prone hillslopes in Rwanda. Precipitation was identified as the most important trigger of landslides and is of course the source of other hydrological processes and stocks such as local and regional groundwater levels and soil moisture content that predispose the slope to near failure. We therefore defined the precipitation-based threshold using rainfall and antecedent precipitation index as a proxy for the soil wetness state. To improve the landslide prediction capability, the regional groundwater level was integrated in the landslide hazard assessment thresholds as a proxy for the catchments storage, an important hydrological processes that predispose the slope to near failure. However, given the scarcity of on-site data, the coarse spatial distribution network of the hydrological and meteorological recording equipment, themselves recording data at point scale, we have tested the potential of satellite and hydrological model-derived information in landslide hazard assessment thresholds in Rwanda.

Results: The defined landslide precipitation thresholds served as an important first step towards the development of early warning system in Rwanda but constrained by the resulting quite high rate of false alarms. The thresholds defined using both precipitation and regional groundwater level as a proxy for the catchments storage significantly improved the landslide prediction capability with high rate of true alarms and low rate of false alarms. Given the scarcity of on-site data, the coarse spatial distribution network of the hydrological and meteorological recording equipment, the rainfall data from Integrated Multi-Satellite Retrievals for Global Precipitation Measurement (GPM_IMERG) was found as a good alternate source of rainfall data for landslide hazard assessment in Rwanda. The hydrological model-derived soil moisture time series broadly reproduce the most important trends of the in-situ soil moisture and proved to be useful for landslide hazard assessment. The hydro-meteorological threshold models that incorporate the antecedent soil moisture content at root zone and the cumulative 3day rainfall reveal promising results.

Conclusions: Based on the overall comparison, the landslide hydro-meteorological thresholds that consider the pre-wetting conditions of the terrain using groundwater levels and soil moisture at the root zone improved the landslide prediction as compared to the exclusive use of the classical precipitation thresholds such as intensity-duration I-D and event-duration E-D. The hydrological processes are concluded to be the most important landslide predictors potentially useful for a robust landslide early warning system development in Rwanda.

SESSION 3.3

RECENT ADVANCEMENT ON SLOPE STABILITY AND DEFORMATION ANALYSIS (PART II)

VISCOHYPOPLASTIC MODELLING OF A CREEPING SLOPE BASED ON INCLINOMETER AND INSAR DATA: PRACKOVICE LANDSLIDE AREA CASE

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Creeping slopes and slow-moving landslides are a common type of slope deformation. Even though usually not catastrophic, they can cause serious damages to infrastructure and even may be a precursor of a rapid slope failures. Modelling of slow-moving landslides and creeping slopes and predicting their rate of movement can provide important information to reduce risk and related costs. However, numerical modelling that accounts for soil mechanical behaviour is scarce in literature, especially when rate-dependent mechanical behaviour such as creep is considered. In this contribution, we present a 2D viscohypoplastic analysis of a cross-section of a creeping slope with highway embankment supported by structural elements (anchored pile wall) in the northern part of the Czech Republic. The modelled area is affected by deep rock block spreading with slow creep deformations of basalt blocks sliding on plastic basal marlstones. The time-dependent viscohypoplastic constitutive model is used to model creep deformations in the shearzone. The modelling strategy is composed of two parts: (1) calibration and optimalization of the material parameters via back-analysis of inclinometer and InSAR measurements; (2) 30-year prediction of slope displacements. Additionally, a parametric analysis of the influence of viscous soil parameters on the predicted displacements is investigated.

A PARTICLE FINITE ELEMENT APPROACH TO SLOPE STABILITY ANALYSIS

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Purpose: The stability of slopes is a critical issue in civil and geotechnical engineering, with significant implications for public safety and infrastructure. In recent years, there has been increasing interest in the development of numerical methods for the assessment of slope stability, with a focus on techniques that can handle large deformations and complex geometries.

Methods: One such method is the Second Order Cone Programming - Particle Finite Element Method (SOCP-PFEM), which has been specifically developed to treat large deformations in continuum mechanics. The method treats the medium as a collection of particles, which are used as nodes for a finite element discretization. In this way, the finite element mesh moves along with the continuum body, allowing for natural tracking of boundaries and interfaces during motion and simplification of boundary condition imposition. The resulting linear problem is equivalent to a second order optimization problem and is solved for the variables of interest. In this study, the SOCP-PFEM method is applied to assess the stability of subaerial landslides using a strength reduction method, which involves gradually reducing the strength of the material to find the Factor of Safety (FOS) of the slope. Both synthetic and real-world case studies are analyzed, and the results are compared with the minimum lithostatic deviation method, an evolution of the classic method of Limit Equilibrium (Tinti and Manucci, 2008).

Results: The results demonstrate that the SOCP-PFEM method produces consistent results with the minimum lithostatic deviation method. However, the SOCP-PFEM method has the advantage of being more adaptable to complicated geometries, which is crucial for practical engineering applications. This advantage is particularly relevant when dealing with real-world slopes, which can have irregular shapes and complex features that traditional methods may hardly handle.

Conclusions: Overall, the study provides evidence that the SOCP-PFEM method can be a valuable tool for the assessment of slope stability. Its ability to handle large deformations, track boundaries and interfaces, and adapt to complicated geometries makes it a promising alternative to traditional methods for the analysis of unstable slopes. However, further research is needed to fully evaluate the strengths and limitations of the SOCP-PFEM method and to assess its performance in a range of practical engineering applications.

STUDY OF LANDSLIDE ON EXCAVATABLE SURFACES USING FINE RESOLUTION DISCRETE ELEMENT SIMULATION

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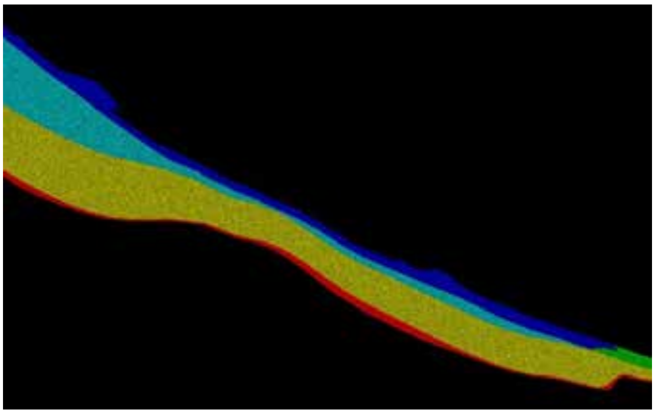
Purpose: Damage to infrastructure and human life can be significant when landslides occur. Understanding of the surface deformation and failure during landslide behavior is essential for accurate hazard assessment and mitigation strategies. However, conventional simulations often treat landslides as a constant mass sliding on a fixed, rigid slope, which does not accurately represent the excavation and erosion of the slope. In this study, we aim to investigate the influence of an excavatable slope on landslide behavior.

Methods: To simulate the slope, considering both the released geomass from the main rupture and the excavatable surface of the slope, we used the discrete element method (DEM) with a bonding model. To generate fine-resolution DEM models, we used a high-resolution digital elevation model for the slope geometry and a newly proposed modeling method called periodic granular (PG) box for discretizing the slope geometry as DEM particles.

Results: Our fine-resolution simulation, compared to conventional simulations using particles a few meters in size, provides a more provides a more detailed description of surface deformation and failure during landslides. We observed surface deformation and failure induced by the initial release of geomass, as shown in Figure 1(a) and (b). Parameter studies were conducted to investigate the influence of particle friction and bond strength on the runout distance. Our results suggest that particle friction is critical in determining the runout distance, and when particles are bonded together to slide, the runout distance becomes larger.

Conclusions: Understanding the influence of inter-particle friction and bonding on landslide behavior is important for accurate hazard assessment and mitigation strategies. Our results suggest that there may be a size segregation where larger blocks occur on top of finer particles. The finer particles essentially act as a lubricating layer, further increasing the runout distance. In addition, some lubricating effects from pore water or liquefaction mechanisms may occur during sliding that reduce interparticle friction. This makes it difficult and necessary to model the decrease in interparticle friction during landslide. Our study highlights the need for further research in this area to improve landslide simulation and mitigation strategies.



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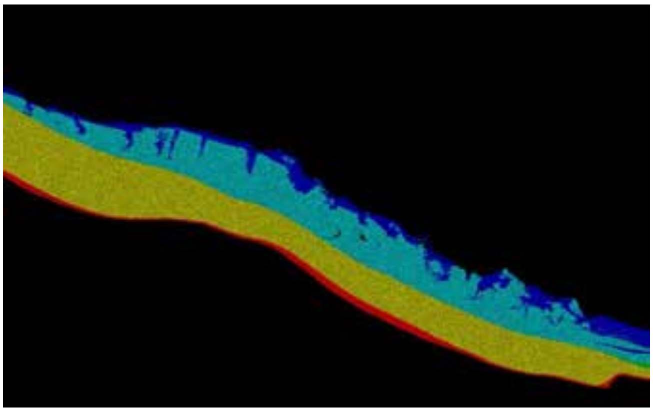

b

Fig. 1: a) an early stage of the landslide; b) surface deformation and failure during the progress of the landslide.

DEBRIS FLOW DAMAGE PREDICTION BY LANDSLIDE FLOW MODELLING

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Purpose: A large numbers of landslide events are reported every year in various part of the world which results in loss of life, destruction of infrastructure, damage to land, loss of tourism and natural resources. Along with that, landslide material can also block rivers and increase the risk of floods. Therefore, there is a need of extensive study of landslide and its kinematic behaviours to reduce the landslide associated damage and take preventive measures. The primary objective of this research work is to identify the danger zones due to debris flow by means of landslide flow modelling. The National Landslide Susceptibility Mapping (NLSM) Data Base, slope and hydrological data are used.

Methods: To accomplish the objective, landslide flow modelling is performed by using RAMMS software. A well-documented debris flow landslide instance previously occurred in Malappuram region of Kerala, India was chosen as the study area. Based on the slope analysis, the stability of the slope was assessed using a DEM with a resolution of 30 x 30 m, and the debris flow initiation zone was calculated by examining the overlap of the drainage system and slope with NLSM map. Initially, calibration of parameters in RAMMS is performed over a known landslide, Puthumala landslide (Kerala), by obtaining best fit to landslide shape and the landslide flow is modelled for four selected high susceptible sites in Malappuram.

Results: As a result of flow modelling, the debris flow path and maximum velocity plots are generated. The obtained results are impressive and areas in danger zones are identified (Figure1 to Figure 4).

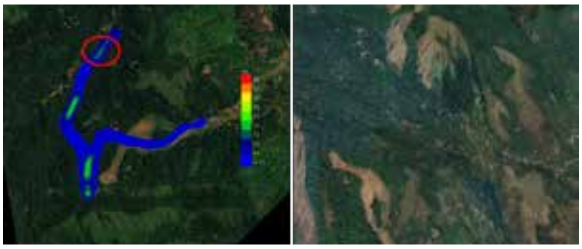

Fig. 1: Predicted landslide flow for site LS1 (left) and the village are falling in the path of landslide (right).

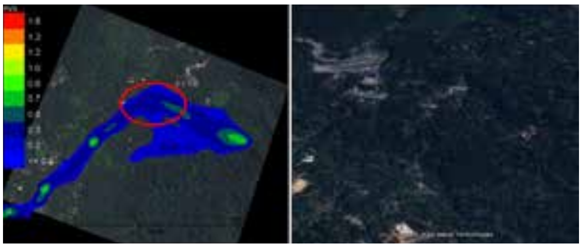

Fig. 2: Predicted landslide flow for site LS2 (left) and the village are falling in the path of landslide (right).

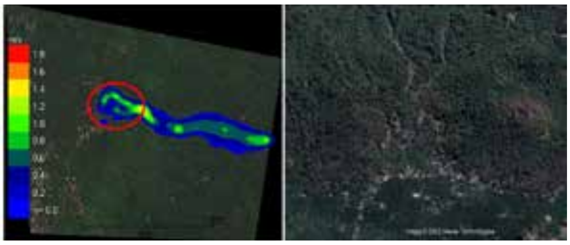

Fig. 3: Predicted landslide flow for site LS3 (left) and buildings in the path of landslide (right).

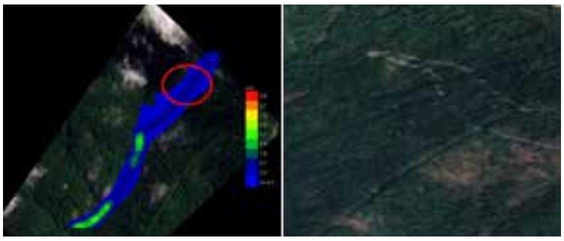

Fig. 4: Predicted landslide flow for site LS4 (left) and the village are falling in the path of landslide (right).

Conclusions: This investigation involves data from the real situation to get very reliable simulation results from RAMMS which could be used for early warning in future and landslide associated losses would be reduced.

R.AVAFLOW GOES SLIDING: EXTENDING THE SCOPE OF THE OPEN-SOURCE MASS FLOW SIMULATION FRAMEWORK

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Scope and objectives: Operational, GIS-supported simulation tools for the dynamic propagation of gravitational mass movements are often designed for extremely rapid, flow-type movements most relevant for risk management, such as snow avalanches, rock avalanches or debris flows, or for fall-type movements. Mass flow models commonly use depth-averaged, more recently also full 3D, mixture or multi-phase approaches. Less attention has been paid to slide-type movements, slow movements, or layered movements. However, appropriate representation of such processes can not only be useful to inform risk management, but also for geo-education in a broader sense. This contribution presents and discusses the extension of the GIS-based, open-source mass flow simulation tool r.avaflow with functionalities for (i) a sliding component, which can be considered instead of or in addition to the flow-type movement, (ii) the capability to simulate layered landslides, and (iii) a viscosity-based equilibrium-of-motion model for landslides and other geomorphic processes which are not extremely rapid. All three functionalities build on intuitive, simplified approaches requiring few model parameters rather than on physically complex approaches based on several, often unknown, parameters.

Case studies: Each of the three functionalities can be used individually, but it is particularly the combination of at least two of them which opens up new possibilities for GIS-based mass flow simulation. Three specific test cases are presented:

1. Prehistoric Köfels rock slide, Tyrol, Austria. The sliding model is employed to back-calculate the motion of this giant landslide with a volume of 3–4 cubic kilometres, which was characterized by sliding with some internal deformation, rather than disintegrating into a rock avalanche.
2. Deep-seated gravitational slope deformation: all of the newly introduced functionalities are combined to simulate a long-term slope deformation in a generic landscape, which occurs along three slope-parallel sliding surfaces. Such phenomena are commonly observed in mica-rich metamorphic rock.
3. Collapse of a volcanic island slope: the example of the 2018 Anak Krakatau event, Indonesia, is used to simulate an island slope collapsing into the sea. The sliding function prevents the immediate spreading of the movement in all directions, whereas the layering function ensures that the landslide deposits at the seafloor and the original sea surface recovers after the displacement wave has alleviated.

Evaluation of the results is supported through a new interface between r.avaflow and the 3D visualization software Blender, allowing for highly immersive virtual reality (VR) scene inspection. Such inspection indicated plausible results for all cases.

Conclusions and outlook: A thorough empirical evaluation campaign with well-documented real-world cases is required as a next step. We expect that our extended r.avaflow model will be valuable for awareness building, geo-education, and general science communication. In combination with the VR interface, it opens up new possibilities for simulating and digitally experiencing landslides, which can be of interest for different groups of users.

Acknowledgements: This work is part of the project "Moving mountains - landslides as geosystem services in Austrian geoparks" (ESS22-24 - MOVEMONT) funded through the Earth System Sciences programme of the Austrian Academy of Sciences.

SESSION 4.8

LANDSLIDE IMPACTS, VULNERABILITY AND QUANTITATIVE RISK ASSESSMENTS OF PEOPLE, COMMUNITIES, STRUCTURES, AND INFRASTRUCTURE (part III)

QUANTITATIVE RISK ASSESSMENT OF THE SHILONGMEN RESERVOIR LANDSLIDE IN THE THREE GORGES AREA OF CHINA

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Purpose: The reservoir landslide developed in the Jurassic red-strata area is a severe geological disaster in the Three Gorges reservoir area in China. Therein, strong external conditions (reservoir water level fluctuation and heavy rainfall) constantly change the active state of reservoir landslides, resulting in substantial economic losses. The current research lacks the quantitative risk assessment framework for reservoir landslides.

Methods: Referring to the case study of the Shilongmen landslide (Wanzhou section of the Three Gorges Reservoir in China), the risk is assessed by considering two hazard scenarios corresponding to the deformation and failure phases. The main innovative features are as follows: (i) The surface displacements of the Shilongmen landslide were simulated by fully-coupled finite element analyses, which take into account the reservoir water level and rainfall as triggering factors of landslide displacements; The hazard intensity in the deformation scenarios was quantified based on the structural combined deformation theory, which quantitatively analysis the vulnerability of the element at risk on the landslide. (ii) The failure probability under different scenarios of annual reservoir regulation and return period of rainfall events via the limit equilibrium method and Monte-Carlo method framework was computed; The landslide dynamic analysis model and physical experiment calculated the tsunami propagation height. (iii) In the deformation scenario, the expected monetary loss is estimated by multiplying the monetary value of the buildings by their vulnerability, and the corresponding risk map displays the potential economic losses to the EAR. In the failure scenario, direct (landslide) and indirect (tsunamis) risks are considered because the rapid decline of reservoir water level and heavy rainfall can cause the landslide rapidly slide into the Yangtze River.

Results: The results show that: (i) The expected monetary loss of the EAR is 771683.1 ¥ in deformation scenarios. The unit price and built-up area give some buildings with low vulnerability a high monetary loss, which can be reinforced through later maintenance. In the vital activity area (e.g., the front area), the cracks caused by surface deformation cannot be solved through building maintenance, and relocation may be the best way to reduce the risk. (ii) The annual maximum failure risk of the Shilongmen landslide occurred in the rapid lowering period of 162 m-145 m water level. According to the economic risk map of the Shimongmen landslide, the landslide risk (1796910 ¥) is lower than the risk of secondary hazard tsunami (2.612 million ¥). The failure of the reservoir landslide not only causes destructive damage to the buildings in the landslide area but also poses a significant threat to the Yangtze River channel.

Conclusions: These models are based on detailed investigation data and long-term research plans. Considering that there are several unstable slopes in the same geo-environmental context in the TGRA, the proposed research framework could provide a reference for government risk management strategies.

STUDY ON FAILURE BEHAVIOR AND VULNERABILITY OF MASONRY STRUCTURES CAUSED BY GROUND CRACKS ON SLOW-MOVING LANDSLIDES

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Purpose: Vulnerability is a crucial factor in landslide risk analysis, and assessments which focus on fast-moving landslides can fail to accurately quantify the risk of slow-moving landslides. To address this limitation, it is important to study the vulnerability of buildings on moving slopes while taking into account the temporal and spatial differences in landslide deformation. This study aims to examine the impact of slow-moving landslides on masonry buildings in the Three Georges Reservoir (TGR) area to illustrate the impact of this phenomenon on the built environment. Importantly, the information and analyses provided the means to develop a quantitative vulnerability model for structures built on active landslide cracks.

Methods: Using a combination of field investigations, physical model testing, and numerical simulation methods, the failure behaviors of masonry structure effected by the shearing ground cracks on the slow-moving landslides are summarized and analyzed. Finally, a quantitative model of vulnerability for masonry structures was established based on fuzzy mathematics and the Weibull function applied on the test data and observations.

Results: (1) A field survey of the building damage was carried out. It was found that the cracks of doors and windows accounted for the largest proportion (37.88%) of those cracks observed, and the floor and the seams accounted for the smallest proportion. (2) A geomechanical model of masonry structure damage under the influence of shearing ground cracks of landslide was constructed which helped reveal the mechanism of building damage caused by slow-moving landslides. (3) A physical model test device for simulating the damage process of buildings on landslides was developed, and physical model test was completed. The damage effects of masonry structures were analyzed and it was found that the damage of the model started from the foundation, and the cracks extended from the foundation upwards along the wall. The macroscopic deformation of the test was consistent with the field observation. (4) The numerical simulations of building damage under the different loading states were completed. It was found that the loading modes leading to higher degrees of damage, from highest to lowest, were tension, shear and extrusion. (5) A criterion for quantifying the damage degree of masonry structure and its quantitative evaluation method were proposed. The vulnerability curves of buildings under the influence of shear cracks on landslide was constructed with a goodness fit of 0.944.

Conclusions: Our results offer a means of quantifying the risks posed to towns and other urban areas on large, slow-moving landslides. Our findings can be used to provide scientific guidance on effective risk management and building planning strategies.

DEBRIS-FLOW STRUCTURAL RISK ASSESSMENT USING A MECHANICAL-BASED VULNERABILITY INDEX METHOD

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Debris-flow represent a severe source of damage and damage for buildings [1]. Procedures based on simplified approaches can provide great help to identify the most vulnerable buildings on areas at risk, in order to undertake retrofit and mitigation actions. In this work we propose a simplified vulnerability assessment method for structures exposed to fast moving landslides.

The proposed strategy is based on assigning a Vulnerability Index to each building and, on the basis of the hazard level, the method gives the most probable damage grade [2].

The main novelty resides in the fact that events are simulated numerically in order to properly tune weights and scores and thereby overcoming the lack of observed data. The numerical simulations are first employed to detect the relevant parameters by evaluating their sensitivity on the structural resistance. For each selected parameter, intervals are identified to assign a vulnerability class and a related score. Then, a large population of buildings and events is generated using a Monte Carlo approach and the VI weights are obtained from the best fit between the Damage Level (DL) estimated by the proposed method and that evaluated through the numerical simulations.

The proposed approach have some similarities with other VI based methods used in the vulnerability assessment to other natural risks, as earthquake and floods [3] and, therefore, it can be adopted for multi-risk analyses.

Results show a good agreement between the proposed simplified method and more detailed numerical simulations, especially in estimating the high or low damage levels.

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MULTISCALE ANALYSIS OF ROCKFALL IMPACT AGAINST STONE MASONRY STRUCTURE FOR VULNERABILITY ASSESSMENT

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Purpose: Rockfall occurrence has been significantly increased in the last years, involving higher risks for transportation infrastructures and settlements. Thus, there is the urgent need to effectively assess and measure the risk in urbanized areas, i.e. to quantify the hazards and the potential damages. The effect of rockfalls on buildings depends on the magnitude of the phenomenon and the properties of the impacted structure, in terms of material, arrangement of the resisting elements and geometry. Limited studies are devoted to investigate the vulnerability of stone masonry structures, which are quite common in mountain environments. To fill this gap, the present work aims at experimentally and numerically analysing the effects of impacting blocks of different magnitude on a vertical stone masonry wall. A study framework is proposed.

Methods: To investigate the effects of impact, a multiscale analysis is adopted. At the microscale, an experimental campaign is performed to identify a contact law for blocks impact to be further implemented in the numerical model. An instrumented impacting plate is used and blocks of different shape and velocity are tested. At the mesoscale, a single wall is numerically simulated through a FEM model and the local damages are determined. A parametric analysis is carried out to encompass various boundary conditions, constraints and wall properties.

Results: Preliminary results are illustrated. It is shown that several parameters affect the response of the impacted wall: construction properties, e.g., wall thickness, presence of mortar, friction between elements, impact position and kinetic energy of the block. For each numerically simulated scenario, collapse vs. non collapse final configuration is assessed with the scope of quantifying the degree of loss on the single element.

Conclusions: An experimental and numerical study to define the local response of a stone masonry wall impacted by a falling rock block is proposed. Interesting findings on the effects are highlighted. The outputs of the study on single stone masonry walls can be used for vulnerability assessments on more complex structures.

A DEEP NEURAL NETWORK MODEL FOR THE FAILURE OF MASONRY WALLS DUE TO ROCKFALLS

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Purpose: To incorporate the vulnerability of buildings into the rockfall quantitative risk assessment, simple tools are required. As masonries are common in mountainous areas, this work provides a mathematical model for assessing the damage of masonry walls when impacted by boulders.

Methods: Artificial Intelligence (AI) methods were applied, according to Mavrouli et al. (submitted). A database was developed that comprises 672 datasets, defined by the values of five parameters: rock block volume and velocity, masonry wall thickness, tensile strength, and the Damage Index (DI) that is the output variable. The database was developed by the application of (i) the Particle Finite Element joined with the Contact Domain Method for the determination of rockfall impact forces, (ii) Finite Element analysis for the calculation of wall stresses and (iii) the modified Von Mises failure criterion for the calculation of the wall damage as DI=Damaged area/Total wall area. The database was split into 448 training, 112 validating and 112 testing datasets and 3.456.000 different architectures of ANN models were trained and developed. The optimum ANN model was selected based on the a10-index and typical performance indices.

Results: The optimum ANN was the LM 4-21-1 model with 24 neurons, optimized by the Levenberg-Marquardt Algorithm, and with the Mean Square Error (MSE) as a cost function. The a10-index was 0.9888 for the training and 0.9911 for the test data. The respective closed-form equation for the Damage Index (DIreal) is given by Equations (1) and (2):

$$\mathrm{DI_{norm}} = \mathrm{tansig}([\mathrm{LW}\{2,1\}]\times[\mathrm{radbasn}([\mathrm{IW}\{1,1\}] \times [\mathrm{IP}] + [\mathrm{B}\{1,1\}])] + [\mathrm{B}\{2,1\}]) \quad (1)$$

$$\mathrm{DI_{real}} = \frac{(\mathrm{DI_{norm}} - a) \times (\mathrm{DI_{max}} - \mathrm{DI_{min}})}{b-a} + \mathrm{DI_{min}} \quad (2)$$

where a=0.00 and b=1.00 are the lower and upper limits of the Min-Max normalization technique; =99.72 and =0.00; tansig and radbasn are the Hyperbolic Tangent Sigmoid transfer function (HTS) and the Normalized radial basis transfer function (NRB). is a matrix with the weights of the hidden layer; , , and are vectors, respectively, with the weights of the output layer, the four input variables, the bias of the hidden layer, and the bias of the output layer. The mapping of the wall damage was provided in graphs (Figure 1).

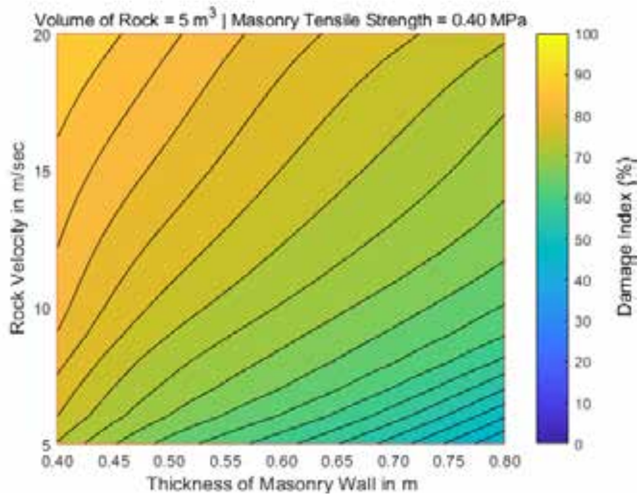

Fig. 1: Damage Index mapping.

Conclusions: The proposed mathematical model can be incorporated directly into the quantitative rockfall risk assessment. This mathematical model is valid for the parameter ranges of the database and does not consider the propagation of the boulders into the building. Both the wall width and the masonry tensile strength have an important effect on the resultant damage.

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AN INTEGRATED MULTI-SOURCE DATA ANALYSIS FOR THE ASSESSMENT OF CONSEQUENCES ON THE SLOW-MOVING LANDSLIDES-AFFECTED BUILT-UP ENVIRONMENT

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Purpose: The main goals of this work concern the characterization of slow-moving landslides (in terms of both geometrical and kinematical issues) and the estimation of the vulnerability of structures (e.g., buildings) and/or infrastructure (e.g., roads) interacting with them. These goals represent key steps for quantifying the risk to facilities provided that reliable input data are available. The latter profitably include information gathered from non-invasive spaceborne remote monitoring (e.g., Differential Interferometric techniques) and virtual surveying (e.g., Google Street view imagery) to be integrated with ancillary multi-source data acquired by adopting geological, geomorphological and geotechnical criteria.

Methods: The approach proposed in this work finds its background on the methodological frameworks developed by the authors on the topic in the last few years within multidisciplinary joint research activities (Peduto et al., 2018; Ferlisi et al., 2021). Briefly, it is mainly based on the integrated analysis of multi-source ancillary, monitoring and surveying data to reach the above purpose.

Results: The approach was applied to the case study of Lago municipality (Calabria region, southern Italy) affected by several slow-moving landslides (Figure 1a) which caused damages to the exposed facilities (buildings and roads, Figure 1b-c). In addition to available deep and surface (GPS) displacement data respectively acquired by inclinometer and GPS instruments, remote sensing data provided by the interferometric (DInSAR) processing of Sentinel-1 and Cosmo-SkyMed radar images (within MEFISTO research project) were used too. The DInSAR-retrieved velocity gradient (Figure 1b-c), jointly analyzed with ground-based geotechnical monitoring, the available geological-geomorphological information and the results of extensive multi-temporal damage surveys – carried out on both buildings and roads virtually and on site – allowed us i) characterizing the slow-moving landslides based on deterministic and/or probabilistic methods and ii) generating predictive tools for estimating the degree of loss (inherently related to the expected damage) of the exposed facilities.

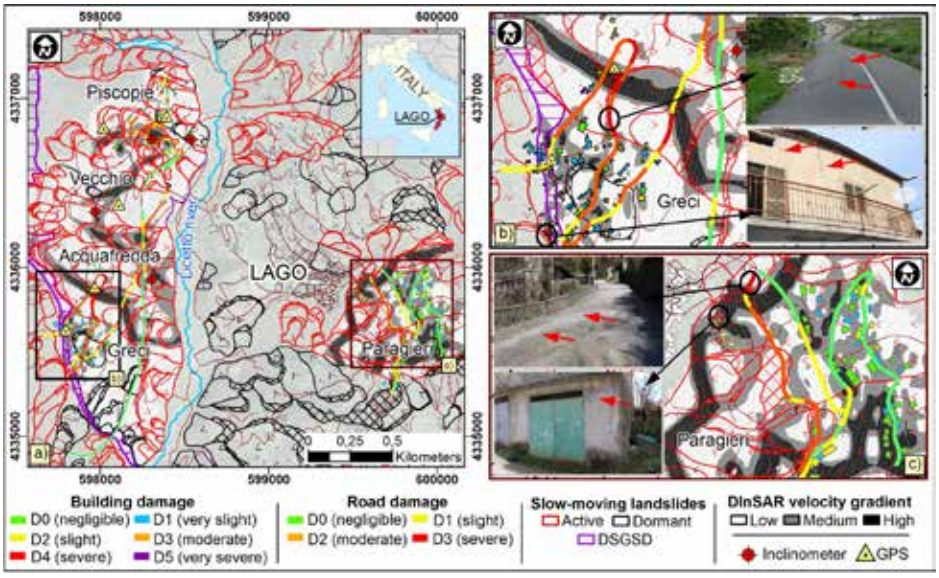

Fig. 1: Lago case study: a) slow-moving landslide inventory map with ground-based (GPS and inclinometers) monitoring and surveyed buildings and road stretches distinguished according to the recorded damage severity levels overlapped to the (DInSAR)-retrieved velocity gradient with some examples for b) Greci and c) Paragieri exposed areas.

Conclusions: Lago case study shows how the analysis of conventional and innovative multi-source monitoring/survey data, if properly integrated according to a multidisciplinary approach, can enhance the studies aimed at addressing two key steps of quantitative risk analyses (i.e., the characterization of slow-moving landslides and the estimation of vulnerability of exposed facilities). Once further validated, the proposed approach could be part of a circular procedure to allow for prioritizing building/road (extraordinary) maintenance activities and scheduling/implementing risk mitigation measures.

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QUANTITATIVE ASSESSMENT OF BUILDINGS EXPOSURE TO LANDSLIDES USING BASIC CENSUS UNITS

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Purpose: The quantitative assessment of exposure of the different types of elements at risk in areas prone to natural hazards is still a challenge considering a quantitative risk assessment framework, as well the transfer of this knowledge to improve regional emergency operations' protocols and to support decision for spatial planners. Regionally, a quantitative assessment of exposure and potential losses is dependent on reliable buildings information, namely the location accuracy and the characteristics of individual buildings. In this study, we explore the potential of the Portuguese Census data to quantitatively assess buildings exposure to landslides in one of the most prone areas in the Lisbon northern region.

Methods: The Information Value statistical method was used to assess landslide susceptibility. Two susceptibility models were constructed according to the slide depth (shallow vs deep-seated) and classified in five classes: very high; high; moderate; low; and very low. The upper limit of each class was defined by the proportion of study area necessary to include the following cumulative landslide area of the landslide validation group: 50; 70; 85; 95; and 100 %. The areas classified with high and very high susceptibility, for both shallow and deep-seated slides, were selected to assess the buildings exposure and the probability of having these very high and high susceptibility (Sp) areas inside a basic census unit (BCU) is given by dividing the BCU area classified with these levels of susceptibility by the total BCU area. Regarding the built environment, through the 2011 Census data it was possible to determine the number of buildings of each type within each BCU. The building type probability (Bp) is obtained by dividing the number of buildings of a given type within a BCU by the total number of BCU buildings. The final probability that a certain building of a certain construction type may be included in an area of high to very high susceptibility to shallow or deep-seated landslides is then given by Sp*Bp.

Results: For simplification, only some preliminary results of the most (RCS - reinforced concrete structure) resistant exposed buildings are presented. In the BCU with more RCS buildings (59 buildings of 64), the area classified with high and very high susceptibility to shallow slides corresponds to 9.6% and to deep-seated slides to 10.6 %. The probability of an RCS building being located over areas classified as more susceptible to shallow or deep-seated slides is therefore 0.09 and 0.10, respectively.

Conclusions: The quantification of the different buildings construction types distribution over hazardous areas remains an ongoing task, particularly for regions where reliable buildings databases are not available. Even considering the uncertainty related to the building's location, the use of the smallest Census units provides a possible way to quantitatively assess regional exposure to landslides of these elements at risk and estimate damage resulting from buildings vulnerability.

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QUANTITATIVE VULNERABILITY ASSESSMENT OF BUILDINGS SUSCEPTIBLE TO SLOW-KINEMATIC LANDSLIDE

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Purpose: An approach for quantitative vulnerability assessment via empirical fragility and vulnerability curves for masonry buildings exposed to slow-kinematic landslide is described. More in detail, the fragility curves express the probability of exceeding a given level of damage for a range of landslide intensity values (Mavrouli et al. 2014). Starting from those ones, the vulnerability curve is recovered, which provides the relationship between the mean level of damage severity to a given (aggregate of) building(s) and the landslide intensity value (Peduto et al. 2017). The results fit within the quantitative risk analysis (QRA), that quantifies the probability of a given level of loss. Moreover, this activity is part of the framework of the DInSAR-3M project, funded by ASI (Italian Space Agency).

Methods: The Department of Earth Sciences of the University of Florence has catalogued the severity damage landslide-induced to over five thousand masonry buildings gathered from in situ surveys in the northern Apennines. Moreover, to retrieve the fragility and consequently the vulnerability curves for buildings, the proposed method exploits the satellite Advanced Differential Interferometry SAR (A-DInSAR) analysis. In particular, such a method considers the landslide intensity value equal to the module of the vertical (up-down) and horizontal (east-west) deformation velocity obtained by properly combining ascending and descending Sentinel-1 P-SBAS (Parallel-Small Baseline Subset) analysis (Manunta et al. 2019). This method to estimate the vulnerability assessment has been integrated within the well-known QRA procedure, which is based on the application of the equation risk (R=H*V*E), where: R is the slope-instability risk; H is the hazard retrieved from the susceptibility map; V is the vulnerability obtained from the equation of the vulnerability curve; E is the exposure of buildings assessed from average real estate market parameters reported in the OMI (Osservatorio Mercato Immobliare).

Results: The method is applied for buildings in Zeri municipality (Massa-Carrara, Italy). The result of the QRA procedure is a risk map, in which for each building is defined the value at risk in economic terms. The analysis provides a total risk of 33.2 million euro and the identification of buildings at highest risk.

Conclusions: A large-scale landslide risk map is produced, in which each building's hazard, vulnerability, exposure and risk are assessed. Specifically, the vulnerability assessment is derived from the probabilistic relationship between the damage severity to exposed buildings and the landslide intensity value. Fragility and vulnerability curves are constructed from a large catalogue of field data and subsequently applied to a specific test site. This procedure can be useful for local administrator to urban management and to identify areas with higher potentiality of damage on structures.

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SESSION 2.12

LANDSLIDE EARLY WARNING SYSTEMS: INNOVATIONS AND APPLICATIONS (part I)

LANDSLIDE DETECTION USING TOTAL GRAY LEVEL METHOD

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Purpose: Landslides are a common natural disaster that can cause significant damage to property, infrastructure, and human life. Monitoring of landslides involves the continuous and systematic observation of landslide activity, including its movement, deformation, and other associated phenomena. Along with ground-based sensors and satellite monitoring, use of image analysis from video recordings is one of the important methods for monitoring landslides and other slope land disasters [1, 2]. These monitoring data can help identify potential risks, assess the magnitude of landslide hazards, and inform decision-making processes for disaster management. With accurate and reliable monitoring, early warning systems can be established to notify communities and authorities in advance of potential landslide events, reducing the risk of loss of life and damage to infrastructure. In today's world of machine learning which consumes high computational resources [3], simple image analysis methods which doesn't consume as much computational power can be a very important tool for detecting landslides [1]. Using total gray level method which calculates and compares the change in total gray level intensity of an image for detection can be one of the effective methods.

Methods: To analyze whether the slope in the recording image is sliding, we select a tracking block (Region of interest, ROI) to limit the analyzing area in the recording image. The average grayscale changing rate in ROI was calculated as an indicator. A substantial indicator change indicates a large temporal variation of the average grayscale in ROI, and the sliding event is detected. The environment grayscale changing rate in ROI is usually a constant value with small noise within 1 min before the event. Therefore, we define the detection threshold using the five times maxima value from the past 1 min. Besides, the sliding event is detected once the indicator continues passing through the detection threshold for more than two seconds.

Results: Preliminary test of total gray level method to detect ongoing landslides has been successful in detecting ongoing landslides with stationary camera position, even from low frame rate videos. Comparatively good results were obtained with the use of minimal computational resources. This method seems to be suitable for shallow landslides where displacement of surface materials is observed.

Conclusions: In conclusion, the use of traditional image analysis techniques such as total gray level method can be a low-cost and effective approach for detecting landslides. Using total gray level method can successfully detect ongoing landslides, even in low light conditions and low frame rate.

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LABORATARY TESTING OF EFFECTS CAUSED BY LANDSLIDES TRIGGERED BY EARTHQUAKES THROUGH UTILIZING FIBER OPTIC METHODS

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Purpose: Landslides are one of the most destructive natural disasters in the world and Turkey, causing significant loss of life and economic problems. There are different applications available today for monitoring landslide and mass movement hazards, such as inclinometers, tiltmeters, extensometers, and ground-based surface digital measurement systems (such as radar, laser scanners, electro-optic, total station, etc.). However, rather than being applied to simultaneous monitoring systems, their temporal resolution depends on the repetition periods. Fiber optic systems are preferred due to their easy and high-speed data transfer, small size and lightweight, sensitivity to unit deformation and temperature changes, ability to work with a wide bandwidth, resistance to environmental and electromagnetic effects, low cost, and ability to perform simultaneous monitoring. These technical features reveal that fiber optic systems can be utilized as early warning systems. The purpose of this study is to develop a fiber optic based laboratory-scale landslide simulator to evaluate the deformation originated from the landslide movements triggered by earthquakes from different perspectives. Following the laboratory studies, the aim is to project it to a fiber optic landslide monitoring station that has the potential to be applied reliably in landslides, especially in earthquake prone areas, that tend to threaten the safety of life and property.

Methods: The deformations on the landslide failure surface caused by the dynamic triggering mechanisms produced by the shaking table that was set up in the laboratory were investigated by the designed fiber optic system. Thus, the sensitivity of the fiber optic cables was tested from different perspectives by using the landslide simulator set up at a laboratory scale. As a result of these studies, sensitivity analyses regarding the selection of the optimum fiber optic cables for a real-time landslide area were performed. The fiber optic system measurements were correlated with the deformation measurements gathered by using potentiometers (LVDTs) and image processing techniques in a laboratory environment for evaluating the reliability and suitability of the fiber optic system.

Results: Tests were carried out at shaking table velocities of 150 mm/s and 200 mm/s; additionally, the amplitudes were optimized within the range of 50 to 170 mm in one direction. Upon analyzing the results, it was demonstrated that the fiber optic cable having a 2 mm diameter measures 10000-15000 με for approximately 1 mm deformations in the experimental setup. The landslide simulator system used in the laboratory study presented convenient results and the findings of the data analysis performed following the use of all experimental techniques have demonstrated that there is a suitable correlation between the physical measurements, the outputs of image processing, and the measurements of fiber optic cables.

Conclusion: In summary, a laboratory-scale landslide simulator was successfully developed and tested. The main triggering mechanism of this simulator was the artificial dynamic loads created by the shaking table using two different experimental methods. The results of the data analyses concluded that the findings of the utilized different methods (physical measurements, image processing outputs, fiber optic cable measurements) are comparable.

HELLOMAC: AN INNOVATIVE EARLY WARNING SYSTEM FOR ROCKFALL PROTECTION SYSTEMS AND EVENTS

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Purpose: Early Warning System and alarm transmission through radio signal and satellite/GPRS coverage.

Methods: Deformation detections.

Results: Alerting people promptly if an event occurs.

Conclusions: The paper describes an innovative alerting system (Early Warning System) developed to verify if a rockfall or debris flow protection systems is impacted or if an event, such as landslides or rock fall, might happen. This new type of system is composed with a device (HelloMac), directly installed on the rockfall/debris flow protection structure or on the landslide or unstable rock surface, and an acquisition unit (Hubir) able to collect the data of up to 100 devices in a radius of 5 km and transmit an alerting message by satellite and/or GPRS. The HelloMac is robust, compact and light (8kg) and it can be easily installed by a crew. The system can be managed with a user-friendly application directly on the smartphone or with a web platform. The system can be calibrated according to the type of protective system, event and requirements for every specific site. It works by detecting the deformations and an alarm signal is immediately notified, also in remote areas with no phone-network coverage. The paper describes in detail the system, its different applications and it presents a very interesting installation done in the French Alps along a strategic National Road (RD 900) connecting France with Italy through the Col de Larche. In this case 17 HelloMac units have been installed and connected with alerting systems (visual panels, traffic lights) placed directly along the RD 900 road.

A NEW METHOD FOR IDENTIFYING THE ONSET OF LANDSLIDE ACCELERATION BASED ON THE EXPONENTIAL MOVING AVERAGE

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Purpose: Predicting the landslide failure time is considered a challenging work in the field of landslide research. Inverse velocity is a widely used in prediction failure time of landslides as its effectiveness and convenience. The onset of acceleration has crucial effect on the prediction failure time from inverse velocity method. For this reason, the study presents the application of a simple method developed to identify onset of acceleration based on exponential moving average, which is widely used in the field of economics.

Methods: The method consists of three steps, and each step is detailed below. (1) Absolutely velocity value; (2) Define the trend change index ω and identify the accelerated trend zone by moving time window technique; (3) Linear regression analysis is performed on the inverse velocity of accelerated trend zone and the OOA point is identified by the correlation coefficient.

Results: Taking the Qubuga landslide occurred in Huize County, Yunnan province, China as an example, only one OOA point was identified based on the proposed method. Furthermore, linear fitting was performed on the inverse velocity of data following the identified OOA point, and the predicted results are < 4 days later than the actual failure time. In addition, the accuracy rate of the predicted results is 96.4%~98.7% and that the coefficient of determination (R2) is 0.92~0.98.

Conclusions: The accuracy of OOA points identified by the method is verified and the result indicates that the method is useful to identify the OOA points. Meanwhile the correlation coefficient is above the 0.9 and the accuracy rate is above the 95%. Meanwhile, accuracy rate and the coefficient of determination show a good correspondence and the improvement of correlation coefficient will improve the prediction accuracy.

SMART BOULDERS TO TRACK THE ACTIVITY ON A SLOW-MOVING LANDSLIDE. INSIGHTS FROM LAB EXPERIMENTS

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Purpose: Landslide hazard has become increasingly problematic due to climate change and population growth, making more people vulnerable to slope failures. As a consequence, the need for effective early warning systems and improved understanding of the underlying processes is critical. The recent development of the Internet of Things and Wireless Networks has opened new possibilities to monitor landslide motion in geomorphology applications. One example is the increasing use of smart sensors embedded in individual boulders to track their movements to gain insight in the mechanics of slope failure and improve prediction models to generate early warning and protect vulnerable communities. Smart sensors are small, lightweight devices that collect environmental data with low power and communicate with a server via wireless connections. However, the reliability of these smart sensors needs to be evaluated and it is still necessary to assess, for example, their life span in different conditions, which type of data can be collected, what are the factors that influence the quality of the transmission, and which filters need to be used to analyse the data.

Methods: In the present study, dedicated laboratory experiments were designed to assess the ability of the sensors to detect movements and distinguish between intensity and type of movement (e.g. sliding or rolling) within a well-constrained setting. For this purpose, a tag equipped with an accelerometer, a gyroscope, and a magnetometer sensor has been installed inside a cobble of 10.0 cm diameter within a borehole of 4.0 cm diameter, closed hermetically before each experiment. The experiments consisted in letting the cobble fall on an experimental table composed of an inclined plane of 1.5 m, followed by a horizontal one of 2.0 m. The inclined plane could be tilted at different angles (18˚- 55˚) and different types of movement have been generated by letting the cobble roll, bounce, or slide. Sliding was generated by embedding the cobble within a layer of sand. The position of the cobble travelling down the slope was derived from camera videos by a tracking algorithm developed within the study.

Results: Raw sensor data allowed the detection of movement and the separation of two modes of movement, namely rolling and sliding. Furthermore, raw datasets approximated the magnitude of movement even without any calibration. On the other hand, by coupling smart-sensor measurements and camera-based positions, it was possible to develop a filter to derive reliable values for the position, orientation, velocity, and acceleration to fully represent cobble motions. The cobble movements were compared to theoretical results computed with simple conceptual framework, confirming the range of movements observed in the experiments.

Conclusions: These findings show how raw data can provide information about the type and an indication of the magnitude of movement, confirming the potential to use these sensors to improve early warning systems. The results also highlight how innovative digital technologies need to be developed along with continuous and careful validation with laboratory and field experiments to fully unfold their potential.

REVIEW OF PRE-WARNING SYSTEM OF LARGE-SCALE LANDSLIDE IN TAIWAN

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Purpose: Soil and Water Conservation Bureau (SWCB) proposed a ten-year plan, "Large-scale Landslide Disaster Prevention and Mitigation under Climate Change," in 2017 to establish a compound response system of large-scale landslide (LSL) and debris flow.

Methods: Based on the spatial relationship with debris flow, potential LSL areas were categorized into two warning types. Type 1 refers to those potential LSL areas that have overlapped protected targets with debris flows while others fall into type 2. (1) Type 1: Those that overlap with existing debris flow protected targets. The responsive preparedness method should continue the existing debris flow preparedness operations, giving due reference to the results of the large-scale landslide impact area designations and updating the existing evacuation procedures. When is-suing alerts, they should be announced in conjunction with the existing debris flow contingency mechanisms and evacuations issued with reference to the current red–yellow warning system for debris flow. (2) Type 2: Those that have no overlap with the existing debris flow protected targets. In response efforts, reference should be made to the results of the large-scale land-slide impact area to increase the warning zone scope and develop new evacuation procedures. Warnings should be issued based on rainfall or other observational data, and on-site evacuation mechanisms should be established.

Results: A total of 9 incidents have issued large-scale landslide warnings in the past two years. Local people took evacuation based on the pre-warning information, and no casualties has been reported. However, partial damage occurred in some potential areas, resulting in the need to revise the existing rainfall warning benchmark value. This study uses the field observation data, such as surface deformation, to quantify the activity status of the potential area. The activity of the potential area is classified by the results of strain and strain rate analysis. The result could show well consistency between the classified and field condition.

Conclusions: The results showed that the rainfall warning value can achieve the positive goal of making people leave dangerous areas during the typhoon and heavy rain events. The activity classification results of the on-site surface monitoring equipment can still serve as the references to adjust or lift the LSL alerts.

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PERMANENT SLOPE MONITORING USING THE ON-BOARD DATA PROCESSING CAPABILITY OF STATE-OF-THE-ART TERRESTRIAL LASER SCANNERS

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Purpose: Permanent Slope Monitoring using the On-Board Data Processing Capability of State-of-the-Art Terrestrial Laser Scanners

Methods: In many regions of the world, especially in Europe, even alpine terrain is densely populated. Settlements, infrastructure - such as roads and railways - are abundantly present and need to be protected by structural measures against corresponding dangers, such as rockfall, mudflows and avalanches. To establish permanent geo-monitoring helps to increase the safety of these regions which are often – e.g., as tourism centers - very important for economy of the country. Terrestrial LiDAR offers effective solutions for such permanent monitoring applications.

Results: Latest developments in the field of terrestrial laser scanners include hardware processing that enables the execution of different background tasks (such as point cloud registration, geo-referencing, orientation via integrated Inertial Measurement Unit, etc.) on-board in parallel while simultaneously acquiring scan data. This on-board data processing capability can also be utilized within apps running on the scanner for customized data-processing workflows. Especially with regard to surface monitoring, RIEGL uses the capacity of their VZ-i Series laser scanners and offers the so-called "Mining Apps" as a bundle, including the Monitoring App, the Design Compare App and the Slope Angle App. The Monitoring App calculates changes to a given reference scan. This allows to detect movements of e.g., landslides long before they are visible to the human eye. The interpretation of these movements through a time series of scans allows the prediction of a possible slope failure. The Design Compare App works similar to the Monitoring App. Instead of a reference scan a given design model defines the reference. As a result, over- and under-cuts to the given design model are visualized. The Slope Angle App calculates the local slope angle from the scan data and visualizes the results.

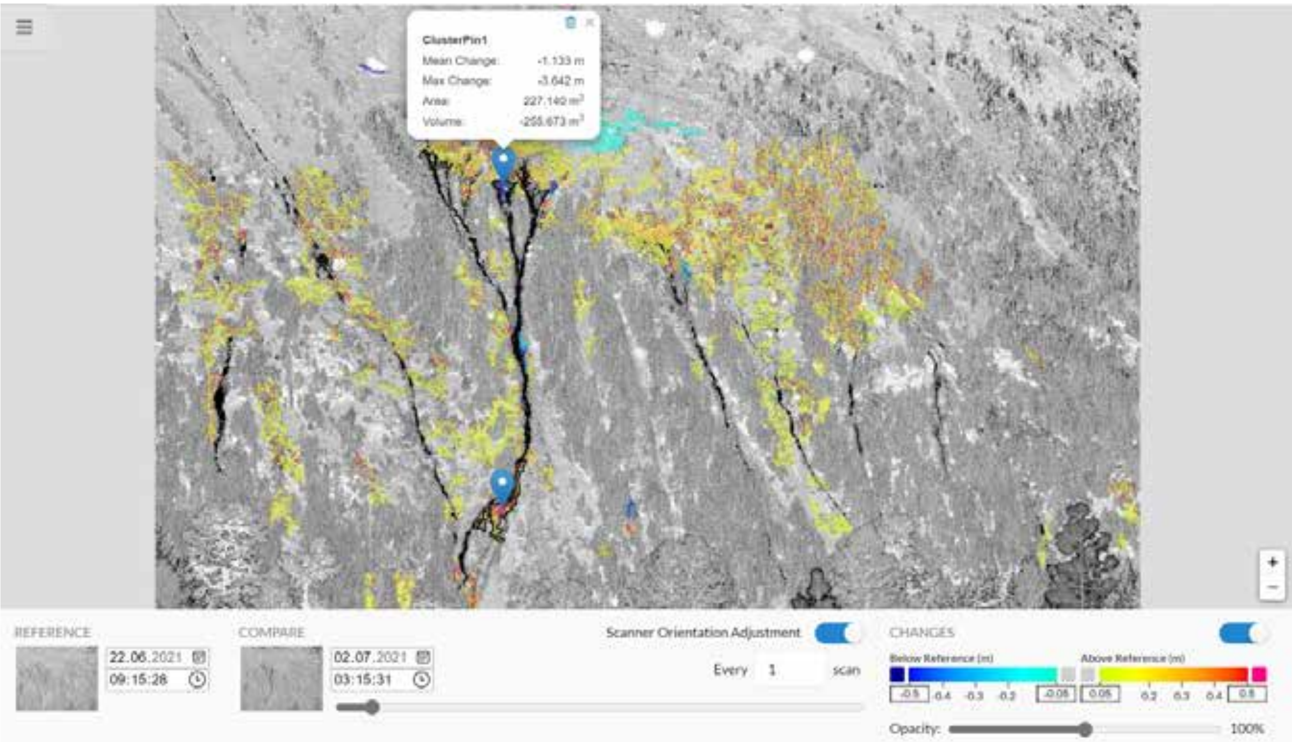

Fig. 1: Web browser-based result from Monitoring App.

All of these apps produce a web browser-based result (see Figure 1). The web server runs on the scanner hardware, allowing the user to view the results with any standard web browser without installing additional software. Alternatively, the result data can be automatically synchronized to the cloud for worldwide publication on a website. Furthermore, complex scheduling tasks for scan data acquisition can be defined. This also enables the automatic monitoring of prisms. An auto-generated csv-file containing the coordinates and range of the scanned prism is ready to be utilized in any standard prism monitoring software solution.

Conclusions: These new developments for on-board data processing and the generation of automatic, web browser-based end results open the door for permanent, efficient and effective 24/7 monitoring by making use of RIEGL laser scanners' capabilities. The presentation will give an insight into the technology and its application by means of first projects.

DEEP LEARNING FOR LANDSLIDE DISPLACEMENT FORECASTING: A COMPARATIVE STUDY

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Purpose: The development of accurate early warning systems for landslides is critical for reducing the risk of fatalities and economic losses. Machine learning techniques, specifically Deep Learning (DL) models, have demonstrated exceptional predictive capabilities for this purpose. Although comparisons of DL models for landslide prediction have mainly focused on Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU) algorithms, other DL methods are also well-suited for time series forecasting tasks.

Methods: In this study, deformation measurements and rainfall time series are used to train seven DL algorithms to forecast future landslide displacement. We evaluate and compare seven DL algorithms, including Multilayer Perception (MLP), LSTM, GRU, 1D Convolutional Neural Network (1D CNN), 2xLSTM, Bidirectional LSTM (Bi-LSTM), and a hybrid 1D CNN-LSTM architecture (Conv-LSTM), for forecasting future landslide displacement. Our investigation focuses on four landslides with varying geological and geographical conditions, monitoring techniques, and time frequencies, with two located in artificial reservoirs and two influenced only by rainfall.

Results: Our results indicated that MLP, GRU, and LSTM models performed well in all four scenarios, with the Conv-LSTM model demonstrating superior performance for the highly seasonal Baishuihe landslide. We observed no significant differences in performance between landslides located in and outside of artificial reservoirs. Additionally, we found that MLP was better suited to forecast larger displacement peaks, while LSTM and GRU were better suited for smaller peaks.

Conclusions: These findings have significant implications for the development of a DL-based landslide early warning system (LEWS). The study demonstrates that DL models can make a significant contribution to forecasting landslide displacement, which might make implementing a DL-based LEWS highly advantageous.

AKHDEFO SOFTWARE: A TOOL FOR LAND DEFORMATION MONITORING USING DAILY SATELLITE OPTICAL IMAGERY

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Purpose: Monitoring land deformation such as natural slope failure in unstable mountainous terrains close to economic infrastructure and communities is critical to reducing loss of life and mitigating damage to infrastructure. Since the early 1990s, satellite remote sensing, particularly Interferometric Synthetic Aperture Radar (InSAR), has been used extensively to monitor slope instability. However, high cost, computing processing capacity and innate constraints of InSAR such as spatial resolution, Line of Sight and frequency of data acquisition can limit its application. These limitations can be overcome by integrating complimentary techniques such as ground-based geodesy and remote sensing (e.g., Radar, Lidar), as well as optical satellite imagery. In this study, we upgraded the AkhDefo software functionality (Muhammad et al. 2022) to monitor and measure near-real time deformation rates of two different regions: 1) The Alpine-glacial Plinth-Peak and Mosaic slopes of the Mount Meager Volcanic Complex(MMVC), BC, Canada; and the 2) Mud Creek landslide on the Big Sur coast of California, USA.

Methods: AkhDefo software uses optical flow velocity to calculate the apparent motion of objects and surfaces between two different timeframes caused by relative motion between the observer (ground-based camera or satellite) and the scene (e.g., objects, surfaces, and edges). In this the study, we processed daily ortho-rectified PlanetScope optical imagery from Planet Lab. The current version of AkhDefo can perform end to end Python-based GIS and image processing and customized generation of figures for publication. AkhDefo has the ability to ingest Planet Lab raw satellite imagery for data preparation, processing, and creation, interactive visualization, and interpretation of deformation map products (Figs. 1, 2, 3). Finally, a validation step includes processing time-series radar imagery using ISCE2, and Mintpy software (Figure 2) to compare and validate deformation maps from optical imagery.

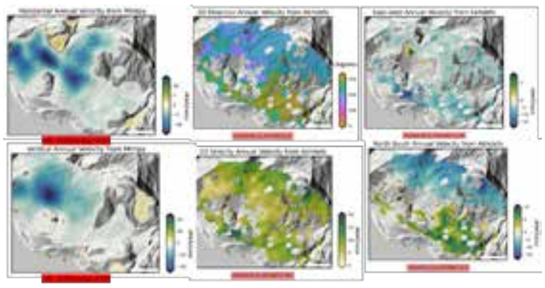

Fig. 1: Deformation maps from InSAR and optical imagery for Mud Creek landslide, California, USA.

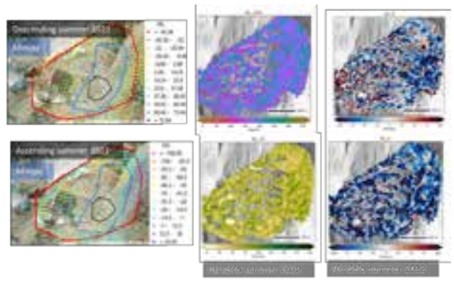

Fig. 2: Deformation maps from InSAR and optical imagery for the Mosaic slope on the MMVC, BC, Canada.

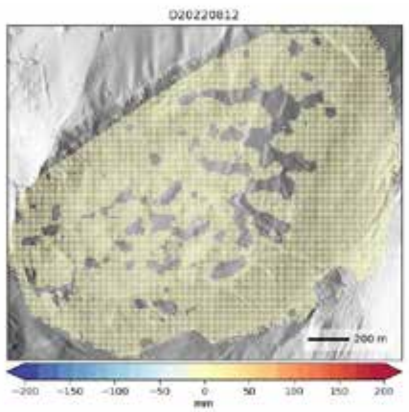

Fig. 3: Deformation maps from optical imagery for Plinth Peak slope on the MMVC, BC, Canada.

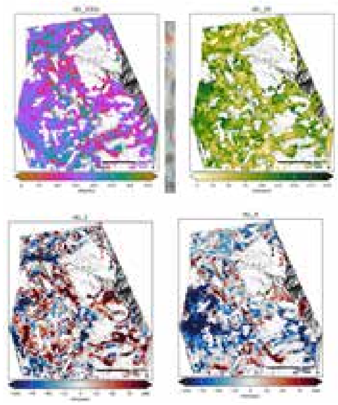

Fig. 4. Time-series Deformation Map-animation for Mosaic slope on the Mount Meager Volcanic Complex, BC, Canada.

Results: Time series deformation maps between February 2020 and August 2022 from InSAR and optical satellite imagery for the Mud Creek landslide show deformation rates less than 20 mm/year. For the MMVC, annual deformation rates calculated based on the summer 2022 InSAR and optical data reached their maximum (200 mm/year) during late August 2022 for both the Mosaic and Plinth Peak slopes. The advantage of this technique is production of low-cost near-real time (daily) deformation data with high spatial resolution (Figure 4).

Conclusions: In this study, we present a further development and application of computer vision and satellite optical imagery for land deformation monitoring. The development includes building a stand-alone open-source geospatial Python library.

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RAINFALL THRESHOLDS FOR DEBRIS FLOW OCCURRENCE IN FOUR CATCHMENTS OF CAMONICA VALLEY, ITALIAN ALPS

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Purpose: In mountainous regions, debris flows cause extensive damage and several casualties every year (Guzzetti et al., 2005). Rainfall is the main initiation process of relatively small debris flows (103-105 m3) occurring in catchments characterized by high sediment availability. Determining critical rainfall thresholds that initiate debris flows is important for the development of early warning systems. The definition of the thresholds can also enhance the knowledge of the hydrometeorological control on debris flows across different climatic and geomorphic settings (Hürlimann et al., 2019). In this work, we analyse the rainfall events that caused debris flows in 4 monitored catchments located in the Camonica Valley (Lombardia, Italian Alps) in 2021 and 2022.

Methods: The monitored catchments, Rabbia, Blè, Cobello, and Re, are instrumented with rain gauges, geophones, infrasound sensors, flow-depth sensors and rainfall-triggered video cameras. The Rabbia and Blè catchments are of primary interest in this study, with a drainage area of 13.5 and 3.5 km2, a maximum elevation of 3,220 and 2,527 m a.s.l., and a main channel length of 5.5 and 2.9 km, respectively. Both basins were recently affected by debris flows which caused severe damages to transport infrastructures. Specifically, the Rabbia catchment was interested by four debris flows from 2006 with a magnitude ranging from 100,000 m3 to 300,000 m3; and the Blè catchment by five events since 2018 with a magnitude between 20,000 m3 and 100,000 m3. Historical information was combined with the data gathered by field monitoring systems to establish rainfall thresholds for debris flow occurrence. This involved categorizing all rainfall events that occurred in the summers of 2021 and 2022 according to the hydrological response that was observed. The identification of the rainfall events was performed by an automatic algorithm that considers the no-rainfall period as a period of less than 0.2 mm of rain in one hour. The time-lapse video cameras allowed to identify the response of the channel. Seismic and infrasound information were used to characterize the hydrological response.

Results: Rainfall events were categorized into the four following classes:
- No increase in water level,
- Increase in water level without sediment transport,
- Increase in water level with sediment transport,
- Debris flow.

Each rainfall event was also classified based on the seismic and infrasound data. Peak amplitude and duration of the signals produced by channel processes connected to each rainstorm were extracted and compared. Critical rainfall thresholds were calculated in each of the four monitored catchments.

Conclusions: These analyses, although performed over a short period of time, provided a good estimation of the combination of rainfall average intensity and duration that can initiate debris flows and allowed to define operational rainfall thresholds for the monitored basins.

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SESSION 1.3

CASCADING MULTI-HAZARD RISKS: SUBMARINE LANDSLIDES, TSUNAMIS, AND IMPACTS ON INFRASTRUCTURES (part I)

TOPOGRAPHY EFFECTS ON LANDSLIDE DYNAMICS AND GENERATED TSUNAMIS

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Purpose: Landslides and generated tsunamis represent some of the costliest geo-hazards and a growing threat to human life across the globe as a result of climate change and population growth. The trajectory and dynamics of gravitational flows such as landslides or debris flows is mainly controlled by topography variations, channeling the flow within valleys or placing obstacles in their way. Describing accurately these effects in landslide and tsunami simulations requires huge computational cost but is necessary to build accurate hazard maps. For these reasons, approximate models have been developed based on depth-averaging of the equations and the shallow layer approximation. However, the formal derivation of shallow equations for general topographies is not straightforward. The curvature of the topography results in a force that maintains the velocity tangent to the topography and a curvature term appears in the bottom friction force (Peruzzetto et al. 2021).

Methods: With the SHALTOP numerical model, we quantify here their influence on flow dynamics and deposits over synthetic and real topographies. Using the code HySEA that does not incorporate these curvature terms we estimate their impact on the generated tsunami waves (Poulain et al. 2023).

Results: Our simulations show that neglecting the curvature force increases the simulated travel times by up to 30%. When the curvature in the friction force is neglected, the travel distance may be increased by several hundred meters on real topographies. We observe similar effects on synthetic channels with a 50% increase of the kinetic energy. Comparison of the simulated force generated by landslides with the force inverted from low frequency seismic data also shows the strong effect of topography related forces in landslide dynamics (Moretti et al. 2015).

Conclusions: Curvature effects can thus have significant impact for model calibration, overflows prediction, and for generated tsunamis all being critical for hazard assessment.

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MODELING VOLCANIC MASS MOVEMENTS AND ASSOCIATED TSUNAMIS AT STROMBOLI VOLCANO (AEOLIAN ISLANDS, ITALY)

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Stromboli is an active volcano of the Aeolian archipelago, in the Southern Tyrrhenian Sea. It is known by its relatively low-intensity, regular, explosive "Strombolian" activity; this ordinary behavior is interleaved by lava flow emissions from the summit craters and by episodic major and paroxysmal eruptions. The ordinary activity constitutes a relatively small hazard for the island, and a spectacular natural phenomenon attracting thousands of tourists every year. On the contrary, major explosions and paroxysmal eruptions represent a serious threat because of the associated intense ballistic fallout and potential avalanching of pyroclastic material on the volcano slopes.

Most of the products of the explosive activity are accumulated on the Sciara del Fuoco, a steep slope area on the North-Western sector of the volcano. These unconsolidated sediments are eventually destabilized by the rapid accumulation of eruptive products during major and paroxysmal events, by lava overflows, or by edifice deformation associated with shallow magma dike migration. The associated volcaniclastic mass flows are able to generate tsunamis at their entrance in the sea, potentially affecting highly frequented shores of the islands typically not threatened by primary volcanic activity.

On December 30, 2002, during an intense effusive activity, a compound submarine and subaerial landslide was triggered on the lower part of the Sciara del Fuoco, generating a tsunami, which in a few minutes heavily impacted the islands shores, with runup exceeding 10 m in some places. While the damage to infrastructures was severe, its occurrence in winter time fortunately had no impact in terms of human lives. That event triggered a renewed interest by the scientific community and civil protection authorities in the quantification of the hazard associated with potential generation of tsunami by landslides and pyroclastic avalanches at Stromboli.

Here, we summarize the work done in the last years to model the generation, propagation and tsunamigenic capability of volcaniclastic mass flows at the Sciara del Fuoco in Stromboli. We discuss the problems associated with the physical and numerical modeling of pyroclastic avalanches and the generation and propagation of tsunamis across the steep and complex topo-bathymetry of the island. We present here the elaborations of an ensemble of more than five hundred numerical simulations and hazard scenarios produced to encompass the range of uncertain landslide volume, initial position and density. A sensitivity study is also presented to evaluate the effects of physical and numerical parameters on model outputs.

Since 2008, a monitoring system has been deployed at Stromboli to detect tsunamis proximal to the Sciara del Fuoco. The two gauges were able to measure sea waves triggered by the entrance in the sea of pyroclastic avalanches generated by two paroxysmal eruptions in July and August 2019, and a sequence of landslide-generated tsunamis from October to December 2022. We present preliminary modeling results where the combination of signal analysis and numerical modeling provide new insights into the dynamics of landslide-generated tsunamis on volcanic islands, and useful information to design an effective risk mitigation strategy for Stromboli.

RESEARCH ON DYNAMIC MODELS OF WAVE GENERATION CONSIDERING LANDSLIDE-WATER INTERACTIONS FOR LANDSLIDE GENERATED WAVES AND ITS NUMERICAL SIMULATION

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Purpose: Landslide generated waves in reservoir are highly hazardous to the safety of the reservoir navigation and hydropower project construction and operation. The wave generation is the starting point of the wave energy spreading and it is vital during the whole landslide generated waves hazard process, but its dynamic mechanism is not very clear till now, which leads to the inaccuracy prediction and limited application of the wave generation model. Therefore, this paper did a research on dynamic models of wave generation considering landslide-water interactions for landslide generated waves.

Methods: We established groups of scaled physical experiments, including gravel sliding test, horizontal drag block generating surge test, and gravel slide generated waves test, deeply observed the process of wave generation and propagation by the impact of deformable debris-like slides and analyzed the feathers of water body dynamic evolution. Comprehensively make use of field investigations data, theoretical analysis and numerical simulation method Tsunami Squares, we proposed three dynamic models during wave generation. To quantitatively verify the correction of the proposed models, the authors imbedded the coupling numerical expressions to Tsunami Squares and simulated the whole process of one group of physical experiments. Comparing the front and side view images shot by cameras with the simulated ones, it shows that landslide speed, moving distance, stoppage shapes, waves generation and propagation shapes are all highly consistent. Besides, all the simulated times-wave height curves also fit well with the ones measured by wave gauges in experiments. Use Tsunami Squares method to simulate two typical landslide generated wave cases, and the simulated values are in good agreement with the survey values.

Results: The three dynamical modes and their coupling numerical expressions for landslide wave generation are proposed, namely Lift Up (LU), Push Ahead (PA) and Drag Along (DA). The good agreement of physical experiment and simulated results verified the reliability of the proposed dynamic model expressions. The good agreement of simulated and surveyed results of landslide generated waves real cases consolidate the reliability of the proposed dynamic model expressions.

Conclusions: This research revealed the dynamic mechanics of landslide waves generation. It can provide accurate input dynamics models for landslide generated waves simulation, and can help to establish more accurate and fast empirical prediction formulas. This research has an important scientific significant and application value for landside generated waves hazard prediction and mitigation.

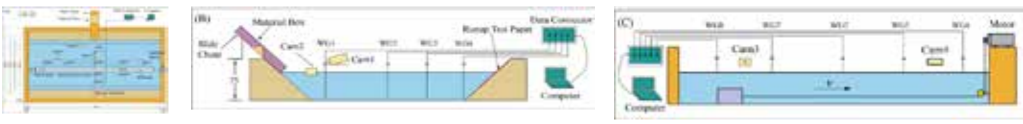

Fig. 1 - A: Plain view of the physical experiments design, B: profile of the gravel sliding test and gravel slide generated waves test, C: profile of horizontal drag block generating surge test.

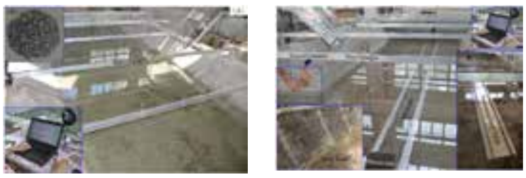

Fig. 2: The scenario diagrams of physical model experiments.

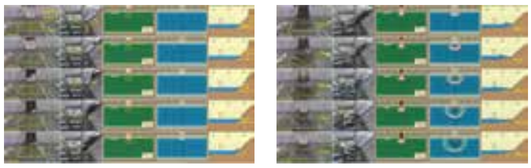

Fig. 3: Tsunami Squares simulation of the whole process of gravel slide generated waves.

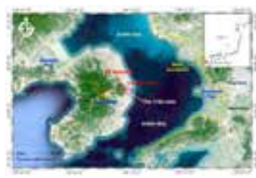

Fig. 4: Location of the Unzen-Mayuyama landslide.

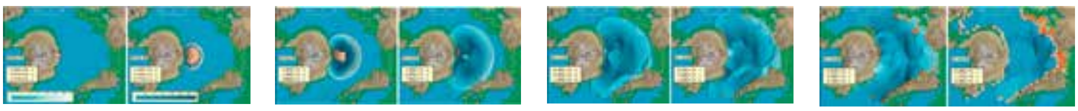

Fig. 5: Eight typical moments of the simulated tsunami.

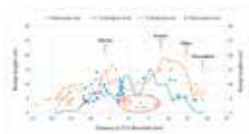

Fig. 6: Comparison of observed and simulated wave runup heights along the shorelines of the Ariake Bay.

A DUAL EARTHQUAKE AND COASTAL LANDSLIDES SOURCE MODEL FOR THE 2018 PALU TSUNAMI INDONESIA

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Purpose: At 10:03 UTC on 28 September, a magnitude 7.5 strike-slip earthquake occurred on Sulawesi Island, Indonesia. Due to its strike-slip mechanism, a destructive tsunami was not generally predicted. However, a devastating tsunami occurred around Palu Bay. Due to the earthquake and landslides, enormous tsunami waves caused more than 4 m of inundation and devastated the City of Palu and the Donggala Regency, resulting in 2,101 deaths. This event is a cascading effect of an earthquake where a primary hazard (earthquake) cascades to other risks (landslide). In this study, a novel dual-source model is proposed for reproducing the 2018 Palu tsunami disaster.

Methods: The previous studies confirmed that both earthquake and landslides most likely generated the tsunami. The authors propose a new dual-source model that combines the existing earthquake and landslide models. It is important to note that the landslide model is dynamic because the seafloor changes over time, while the earthquake model is static. The geometric average K and geometric standard deviation κ proposed by Aida were used to quantitatively compare the measured and simulated run-up height, and flow depth.

Results: Two types of tsunami simulations were performed: (1) Only-earthquake models (simulations based on two published fault models); (2) Dual-source model (combined earthquake and landslide). Earthquake models were conducted using the fault parameters from USGS finite fault and the Jamelot fault. Similar to the previous studies, earthquake model results confirmed that the simulated tsunami run-up height is significantly smaller than the observed data. The dual model can recreate all observed data, especially the high tsunami wave in the South of the Bay. The comparison indexes (K and κ) were calculated to compare the measured and simulated run-up height and flow depth. Overall, the simulation is in relatively good agreement with observation as K = 0.92 and κ = 1.55 for tsunami run-up height and K = 0.96 and κ = 1.47 for flow depth.

Conclusions: From the observed data, the 2018 Palu event indicated clearly that significant strike-slip earthquakes might cause destructive and devastating tsunamis, to which multiple source mechanisms can contribute. This study reproduces all landslide locations inside Palu bay, whose sites are confirmed through previous marine bathymetric and other investigations. The authors proposed a new dual-source model which combines two existing models to simulate the cascading effect of an earthquake. A numerical simulation of the dual model provided a better match with the tsunami observation records than a simulation based on earthquakes alone. It can be concluded that the landslide source rather than the earthquake is the major cause of the local high tsunami inside Palu bay.

ON DOMINANT SUBMARINE LANDSLIDE COMPONENT OF THE TSUNAMI SOURCE MECHANISM AT 1923 GREAT KANTO EARTHQUAKE, JAPAN

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Purpose: The purpose of this study is to understand the mechanism of the tsunami in the Great Kanto Earthquake on September 1, 1923, Japan. The 1923 Great Kanto Earthquake tsunami brought about serious damage to the coastal Kanto region; the tsunami hit from the east coast of the Izu Peninsula to the west coast of the Boso Peninsula in Sagami Bay and caused huge damage. Some fault models were proposed by previous studies and they concluded that a dominant tsunami genesis component was the crustal deformation, however, we found out based on the results of our reproduction simulation of coastal damage that only the fault model cannot explain the observed tsunami records. Here, we show that the dominant component of this tsunami event was induced by the submarine landslides.

Methods: We focused on the records of water depth changes reported by the Imperial Japanese Navy as well as the coastal tsunami traces published in various literatures. Here we present analyzed data of the large-scale seafloor changes before and after the 1923 Great Kanto Earthquake observed at Sagami Bay and the mouth of Tokyo Bay and show the results of a comparison between the coastal tsunami records and the reproduction numerical simulation based on a new tsunami source model induced by submarine landslides, in order to account for a large discrepancy between the actual tsunami records and the predicted tsunamis based solely on the crustal deformation of the 1923 Great Kanto Earthquake in Sagami Bay and the mouth of Tokyo Bay.

Results: We confirmed that the bathymetric changes, which were observed before and after the 1923 Great Kanto Earthquake, corresponded to the submarine valleys of Sagami Bay, based on the analysis and comparison with the current submarine topographic data. The results of the analysis of the bathymetric changes and associated seafloor ground dynamics of Sagami Bay and Tokyo Bay mouth demonstrate that submarine sediments were deposited at the foot of submarine scarps, and significantly outflowed on gentle slopes. On the basis of this finding, we examined the tsunami source model induced by submarine landslides, analysed these records, and found that the new model can consistently explain the observed tsunami heights and the arrival times around Sagami Bay.

Conclusions: Our present study demonstrates that the mechanism of the bathymetric changes observed before and after the 1923 Great Kanto Earthquake is closely linked to the earthquake-induced submarine landslides. Essentially, the new tsunami source model and the results based on this model indicates that the dominant component of the 1923 tsunamis was most likely due to a submarine landslide represented by a liquefied gravity flow. These results highlight the importance of earthquake-induced submarine landslide tsunami risk assessment.

METHODOLOGY TO ASSESS CASCADING MULTIHAZARDS IN NORWEGIAN FJORDS AND THEIR IMPACTS ON INFRASTRUCTURE

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Purpose: Fjords, subsea canyons and mountain lakes often have steep slopes with thick sediment drapes and evidence of prior submarine landslides. One of the major triggers of submarine landslides is earthquakes. Once a submarine landslide is triggered, it can generate debris flows that may impact infrastructure located downslope, undercut infrastructure located upslope, or produce tsunamis that can affect infrastructure on nearby coastlines. Therefore, to ensure safe placement and design, infrastructure projects located in these or similar environments require analyses that account for cascading multi-hazard scenarios such as earthquakes, landslides and tsunamis. However, how to integrate these different types of analyses is not always straight forward. This paper describes a comprehensive and multidisciplinary methodology that integrates earthquake hazard, landslide hazard, and landslide impact analyses. Three example applications from Norwegian fjords are used to highlight the various aspects of the methodology.

Methods: The proposed methodology begins with simplified analyses over the entire project area and uses progressively more advanced techniques focusing on the most critical areas. The general workflow consists of the following analyses: (1) one-dimensional static, pseudo-static and permanent displacement analyses of the entire project area to identify critical locations where landslides could impact proposed infrastructure; (2) static, pseudo-static and dynamic two-dimensional slope stability analyses using the finite element method to refine the identified critical zones and estimate failure volumes; (3) for slopes that do not meet the design criteria, quasi-3D landslide dynamic simulations are performed to calculate landslide runout paths and velocities using the estimated failure volumes; (4) impact forces are calculated based on mass and velocities of landslides at locations of proposed infrastructure. Analyses can be performed for different seismic hazard levels based on regulations or desired earthquake return periods, and design criteria can be based on a factor of safety or soil shear strain level. In addition, the method allows for slopes that do not meet design criteria to also be evaluated for retrogressive failure. Finally, an example back analysis of a previous landslide is described to calibrate input parameters for the quasi-3D landslide dynamic simulations.

Results: For one of the fjords where the methodology is applied, the soils in many locations are unstable and could cause debris flows with long runout distances. The geophysical data clearly support this conclusion. However, for the other two fjords analyzed, the likelihood of landslide impact to the planned infrastructure locations is considered to be low. The examples show the integration of earthquake hazard, landslide hazard, and landslide impact analyses, as well as the flexibility of the proposed methodology depending on the available data and results.

Conclusions: The workflow proposed in this paper is applicable to many offshore geohazard problems, but as the example cases show, the site-specific details govern the way the workflow develops in practice. The work presented here demonstrates the need for comprehensive and multidisciplinary geohazard analyses for infrastructure projects conducted in locations with steep slopes with thick sediment drapes, such as fjords, subsea canyons or mountain lakes.

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COUPLED CFD-MPM ANALYSIS OF THE EARTHQUAKE INDUCED SUBMARINE LANDSLIDES

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Purpose: We present a numerical model that accounts for the interaction between soil mechanics (saturated sediments), fluid mechanics (seawater or air), and solid mechanics (structures) in simulating the entire process of the earthquake-induced submarine landslides.

Methods: The model employs the Material Point Method to handle large deformations of porous media and the Implicit Continuous-fluid Eulerian to simulate complex fluid flows. This allows for the capture of various mechanisms involved in submarine landslides, including earthquake-triggered marine slope failure, excess pore water pressure development, retrogressive sliding, turbulent debris flow, landslide-induced waves, and debris flow impacts on structures.

Results: To validate the model, we have conducted a centrifuge geotechnical experiment at the Port and Airport Research Institute, which captured the transition from slope failure to liquefied flow induced by seismic loading. The numerical model was found to be able to accurately capture the evolution of excess pore water pressure and the transition from slope failure to liquefied flow in a similar way to the centrifuge experiments.

Conclusions: Using the validated model, we investigated different mechanisms of earthquake-induced submarine landslides for different soil states, such as clay versus sand and contractive versus dilative soil. We also used the model to estimate the impact of submarine landslides on offshore structures by considering the triple interactions of saturated sediment, seawater, and structures. Overall, this study provides a comprehensive understanding of earthquake-induced submarine landslides and their potential impact on offshore structures.

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DYNAMIC AND DESTRUCTIVE SLOPE FAILURE OF THE SUBDUCTION ZONE: GEOLOGICAL CONSTRAINS BY SUBMARINE RESEARCHES FROM THE JAPAN TRENCH

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Purpose: The shape and dynamics of the accretionary prism wedge can be explained by the critical taper theory. Since this theory is built using sandbox analogue experiments and soil mechanics, this theory is applicable only to accretionary prisms that are limitedly progressing to the backstop. A recent study proposed his two types of backstops: the Sumatra, Sunda and Java trenches. They are static backstops and dynamic backstops. The static backstop is not moving, and below it is the epicenter of a plate-boundary earthquake. Dynamic backstops are characterized by seismic motion and include forearc basins and outer uplift zones. This paper presents presumable dynamic backstop motion during M9 plate-boundary earthquakes.

Methods: Here, we conduct re-verification of deep-sea images and analysis data, previously reported geodetic data and seismic survey data etc., and infer dynamic backstop motion patterns in the Japan Trench based on them.

Results: In the 2011 Tohoku-Oki Earthquake, slips of up to 20 m were excited upon rupture, and a total displacement of 50 m occurred on the landward trench slope. Such increased slip was thought to be caused by a dynamic landslide at the dynamic backstop, which could extend the slip up to 30 m. The dynamic landslide is thought to have caused the open cracks on the seafloor and the ejection of fluids such as methane observed immediately after the earthquake, and is presumed to have caused a pair of subsidence and uplift on the landward slope.

Conclusions: It is speculated that the dynamic backstop plays an important role in seafloor deformation and is closely related to the tsunami generation mechanism associated with earthquakes. I guess that these phenomena were produced by dynamic and destructive backstop extension. I consider that it excited large-scale slope failures and subsequent tsunamis along the trench. In the future, it is expected that many new findings on dynamic backstops will be released, and the actual situation will be understood in detail.

SESSION 6.4

MACHINE LEARNING APPLICATIONS IN LANDSLIDE SCIENCE (part I)

AN AUTOMATIC DEBRIS SLOPE MAPPING METHOD BASED ON TRANSFORMER ALGORITHM

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Purpose: Debris slope, which is formed during the process of frost weathering, is a type of non-zonal permafrost landform, and widely distributed in high-altitude mountainous areas. It poses a serious threat to slope stability, leading to a chain of geological hazards events such as landslides and debris flows under external forces. Rapid and accurate identification of debris slopes is an important part of evaluating the feasibility of engineering activities and has significant practical implications for site selection and safe operation of major project and infrastructure in high-altitude mountainous regions. However, the technological advancements have not produced powerful automatic mapping tools so far, and the rapid and accurate capture of debris slopes in high-altitude areas remains a challenge.

Methods: To address this research gap, this study first visually interpreted debris slopes along river banks over the Qinghai-Tibet Plateau using high-resolution optical remote sensing imagery from the Chinese GaoFen-2 and Google Earth imagery. Secondly, to achieve the task of automatic identification, we innovatively introduced a new semantic segmentation model, SegFormer, based on the Transformer structure. We also used image processing techniques (Gauss filtering and Cavity filling) to distinguish different instances of debris slopes and remove invalid pixels to further improve the accuracy of identification results. Finally, we compared the SegFormer algorithm with state-of-the-art semantic segmentation algorithms including UNet, Attention-UNet, UNet++, DeepLabv3, FastSCNN, and U2Net.

Results: Firstly, we created a high-precision optical remote sensing image dataset that includes 2000 debris slope samples. Secondly, compared with the other methods, SegFormer achieved the best performance (Accuracy = 94.5%, MIOU = 90.5%, Kappa = 89.84%) thanks to its capability of obtaining much larger receptive field than CNN-based deep learning models.

Conclusions: The result demonstrates the effectiveness of the proposed framework of the automatic debris slope identification, providing an effective solution for intelligent identification task about geological hazards in high-altitude mountainous areas.

Keywords: debris slope, remote sensing, deep learning, transformer, automatic mapping

A PROCEDURE FOR GENERATING GROUND TRUTH DATASET FOR MACHINE LEARNING CLASSIFICATION OF DEFORMATION PROCESSES

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Purpose: The growing availability and accessibility of Persistent Scatter Interferometry (PSI) data pose a challenge to the automatic classification of deformation processes. This study aims to define and develop a comprehensive and objective procedure for classifying ground deformation processes (e.g., landslide, subsidence) detected by multi-temporal remote sensing data. The implemented framework provides a systematic approach for labelling the ground truth of deformation processes in a supervised machine learning (ML) context. The goal is to enhance the accuracy and reliability of automatic classification by providing a trustworthy analysis of the existing phenomena.

Methods: The analysis relies on PSI data points, characterized by time series of displacement along the sensor's Line of Sight (LOS), for detecting and monitoring areas of localized deformation with millimetric precision. The developed methodology takes account of the horizontal and vertical velocity calculated from the vectorial decomposition of the LOS displacement for providing a comprehensive and accurate understanding of the ground movement over time. The areas exhibiting movement are automatically extracted to facilitate the systematic classification process. The classification procedure involved the combination of several data sources, including the mean horizontal and vertical velocity of the movement, geomorphological information layers (e.g., Digital Elevation Model, Slope, Aspect), thematic maps, literature, and inventories of known deformation processes (e.g., landslide inventories) to categorize each phenomenon based on its characteristics and kinematics. The method developed integrates all available data sources in an automatic pipeline to produce a category label and a degree of reliability for each analyzed deformation cluster. Capabilities and accuracies were assessed by validating a subset of labelled processes through direct geomorphological field surveys.

Results: The implemented procedure led to a robust and accurate ground truth dataset. The dataset provides a collection of reliable ground deformations classified with well-defined labels, serving as a benchmark for training, validating, and testing the accuracy and dependability of the supervised ML classifiers. This solid and representative dataset enhances the performances of ML-based classification systems, leading to a more accurate and complete understanding of ground deformation processes. By providing a systematic, objective, and automated methodology, this study has improved the accuracy and efficiency of the ground truth labelling process, successfully reducing both the user-subjectivity and the time required to create the dataset.

Conclusions: ML models have proven to be powerful tools for analyzing and interpreting large datasets, but their effectiveness heavily relies on the quality and quantity of the input data. The presented procedure is a tested and validated methodology for supplying a dependable and robust ground truth dataset of classified deformation processes. This methodology can be extended and applied to other PSI datasets, improving the interpretation of ground deformation processes in various geographical regions and geological settings.
This study was designed and developed as part of the “MUSAR project”, funded by the Italian Space Agency and carried out by NHAZCA S.r.l. (Natural Hazards Control and Assessment) and the Research Center for Prediction and Prevention of Geological Risks (CERI) of the Sapienza University of Rome.

PROOF OF CONCEPT: TESTING THE POTENTIAL FOR AN AUTOMATED, REGIONAL-SCALE LANDSLIDE MAPPING TOOL AFTER SEVERE WEATHER EVENTS OR EARTHQUAKES: CASE STUDY NEW ZEALAND

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Purpose: Provide a case study (New Zealand severe weather events in February 2023) where we retrospectively tested a combination of automated tools for the rapid mapping of landslides over a large area. This event is a unique opportunity given the occurrence of compounding triggers (flooding, Cyclone Gabrielle and several earthquakes) that were reported to have led to an estimated 5,000 landslides.

Methods: In the context of multiple landslide events on the regional scale, data latency is estimated to range from several hours to several days from when a disaster happens and reliable spatial data becoming available to users. This is particularly the case with satellite data and the interpretation of these images also requires considerable effort by specialists. Today, the availability of free spaceborne Earth Observation data products is increasing exponentially, providing the opportunity to exploit additional sources for the rapid generation of a global or regional scale landslide inventory. Our work includes two innovative approaches:
- The use of Artificial Intelligence to continuously mine, in real-time and on the global scale, social media for general landslide related content and images and whose results are available through the Global Landslide Detector (GLD; https://landslide-aidr.qcri.org/service.php).
- The use of a CNN (Convolutional Neural Network) for mapping the failed slope using satellite data: Landslide Tracker. This deep-learning method has been widely successful in extracting information from images and have outperformed other conventional Machine Learning methods (e.g., pixel-based and object-based approaches).

So far, no study has combined these two technologies together.

Results: Landslide images and information were retrieved automatically from social media using the real-time GLD tool. This was used alongside data of the spatial extent of the severe weather events and earthquakes experienced in New Zealand in February 2023. These were used to focus and direct satellite data acquisition for the Landslide Tracker tool to create a map of landslides that had occurred.

Conclusions: This paper demonstrates the potential application of machine learning for landslide recognition in images harvested from social media in real time, allowing for a rapid assessment of where to focus satellite imagery analysis. It also highlights that data latency in disaster scenarios could be lessened considerably through the combination of automated tools, providing information in real-time on the worldwide scale. For this purpose, we created a recent case study image collection from multiple sources with different characteristics to ensure data diversity.

GENERATE AND USE OF SYNTHETIC DATABASE TO TRAIN MACHINE LEARNING MODELS FOR LANDSLIDE MONITORING USING GEOTECHNICAL INSTRUMENTATION

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Purpose: Due to the machine learning is capable of determining patterns within data mass in order to make predictions. It is possible to think that this tool can be used to recognize geotechnical instrumentation signals that can be associated with alert levels within a monitoring system. A machine learning model requires a large amount of data for its training, this data must be organized, cleaned, and labelled so that the machine learning algorithm can learn from it to identify patterns. Besides, for a monitoring approach, the machine learning algorithm should be able to accurately recreate the trends and data dispersion that geotechnical instrumentation equipment may incur. Given the daunting task of collecting such several measurements to train a machine learning model with such characteristics, and which, furthermore, may be applicable to different possible failure mechanisms. It is proposed to computationally generate the model training data, and validate the performance of this approach through landslide displacement data taken from the bibliography study cases.

Methods: According to the creep theory in its tertiary state, prior to failure, the displacement trend, resembles mathematical functions of the parabolic, exponential or logistic type. Therefore, it was proposed that from the mathematical equations of this type of functions, nearly 3000 data series would be generated in Python to simulate the measurements recorded by geotechnical instrumentation equipment. Based on these data series, the machine learning model would be trained. For the purpose of recreating the different failure potentialities in the different data series, the inverse velocity of displacement method was employed. By varying the coefficients of the mathematical equations, different data series were obtained, which resembled different degrees of hazard. The coefficients of the equations were iterated and the resulting data series were evaluated with the inverse velocity method, resulting in different failure forecasts. With the above-mentioned, it was possible to set three ranges of coefficient values, with which failure forecasts of between 0 and 18 hours, 18 and 72 hours and more than 72 hours would be obtained, which associated to three alert levels. Each alert level was generated with a total of 1000 different data series. In order to simulate the variability of the data recorded by the geotechnical instrumentation equipment, a coefficient of randomness was incorporated into the data generation equation, which was obtained from the precision value of the geotechnical instrumentation equipment. The 3000 synthetically generated data were used to train a decision tree machine learning model.

Results: In favor to evaluate the adaptability of the trained model to different specific monitoring cases, the model was validated using 15 slope failure cases. Each one of the 15 cases had a different displacement behavior prior to failure collapse. For model performance metrics, we used confusion matrices that reported accuracy levels higher than 97%

Conclusions: Using mathematical equations, it was possible to develop a synthetic database that would reproduce the deformational behavior of the Tertiary Creep under different levels of acceleration, while recreating the dispersion typical of geotechnical instrumentation data. These synthetic data allowed us to train a machine learning model applicable to geotechnical monitoring plans, whose performance metrics indicate outstanding results.

DEVELOPMENT OF AI ALGORITHMS FOR LANDSLIDES PREDICTION (EMILIA-ROMAGNA REGION, ITALY)

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Landslide risk is one of the most relevant hazards that affects the Emilia-Romagna Region. Almost 80,000 landslides were mapped in the mountainous part, and the percentage of land covered by landslides exceeds in some areas 25%. Although most of the regional landslides are relatively slow, the economic impact is critical: in 2019, 1 million euros was allocated for urgent safety interventions, and it is estimated that at least another 80 would be needed to complete the plan. These numbers place the Emilia-Romagna Region among the areas with the highest landslide risk in the world. The geological characteristics of the Region, combined with the growing exploitation of the territory and the climatic changes underway, are making this problem more and more dramatic. It is now clear that emergency responses are no longer sufficient and that they must be accompanied by prevention actions devoted to mitigating the risk. More efforts are needed to forecast the critical rainfall conditions leading to slope instability as well as to predict the reactivation of dormant landslides and the triggering factors of first-time failures. Unfortunately, such goals are difficult to reach due to the substantial unpredictability of landslides.

The main objective of this work is to develop Artificial Intelligence models for the prediction of landslides in the Emilia-Romagna Region. The idea is to exploit the data collected by the University of Bologna in the last 75 years, as part of the research activities carried out in collaboration with the Regional Agency for Civil Protection and the Geological Survey of the Emilia-Romagna Region.

Machine learning and conventional approaches were applied to the Emilia-Romagna region of Italy using a historical landslide and rainfall data archive. The methods included Bayesian approach, Neural Networks, XGBoost, TPOT, Random Forest, LDA, QDA, and Linear Regression. Results showed that landslides in the area were mostly caused by rainfall event parameters such as precipitation during the event and its location, while antecedent rainfall was found to be less important. The results indicated that a rain event of 90-100 mm was necessary to trigger a landslide after the dry summer season, but this decreased as the day of the year increased. The algorithm had an F2 score test result of 0.54, meaning it could correctly predict a true positive (rainfall causing landslide) every 3 positive instances and correctly predict a true negative (rainfall not causing landslide) 95.5% of the time.

DETECTING TREND CHANGES IN PERSISTENT SCATTERER INTERFEROMETRY DISPLACEMENT TIME SERIES: A COMPARATIVE STUDY AND APPLICATION IN LANDSLIDE DETECTION

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Purpose: Monitoring ground deformation is a crucial task in geohazard management to ensure the safety of lives and infrastructure. Ground deformation can be caused by earthquakes, slow-moving landslides, subsidence due to groundwater exploitation or underground mining, volcanic unrests, and others. Recent advances in remote sensing techniques have made it possible to monitor ground deformation effectively and continuously. Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) is an advanced technique for measuring slight changes on the Earth's surface. Estimated PS-InSAR time series acquired by Sentinel 1 satellites provide a great opportunity for an effective monitoring of ground deformation including slow-moving landslides in recent years. However, challenges arise when processing these time series due to their non-uniform sampling, noise from atmosphere and preprocessing issues during phase unwrapping and others. Therefore, detecting trends in such time series, as an indicator of ground movement, is not an easy task.

Methods: In this work, using both sets of simulation and PS-InSAR time series, we compared four popular time series change detection methods, namely, non-parametric Mann-Kendall and Pettitt sequential change-point detection, sequential linear regression, and jumps upon spectrum and trend (JUST). These methods can statistically determine whether there is any change-point or breakpoint in the time series and can be used for estimating magnitude of trend change in the time series.

Results: We show that JUST outperforms other methods in terms of root mean square error (RMSE) though it has a higher computational cost. JUST simultaneously estimates the seasonal and trend components at a given confidence interval (95% or 99%), allowing a more effective estimation of changes in trend component of the time series. Furthermore, JUST can also consider the measurement errors and does not require any interpolation and smoothing of the time series.

Conclusions: Missing time series values and presence of seasonality can greatly impact the performance of the Mann-Kendall and Pettitt tests, and linear regression, while JUST is a more robust technique which determines whether there is statistically significant seasonality in the PS-InSAR time series, allowing a more robust estimation of trend change in the time series. The trend detection techniques presented in this work can be used for detecting and measuring the magnitude of landslides through PS-InSAR time series and can be integrated into a monitoring system to automatically detect when and where the deformations occurred along with their magnitudes.

STATISTICAL ANALYSIS OF INSAR TIME SERIES USING A MULTI METHOD APPROACH FOR LANDSLIDES IN THE ALPINE REGION

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Purpose: The analysis of time series is of significant importance for a comprehensive understanding of landslides, particularly when movements result from a superposition of multiple environmental triggering factors (e.g. precipitation, snow, temperature). In this context, Synthetic Aperture Radar (SAR) sensors allow monitoring landslides by providing long time series with high spatial resolution. The purpose of this work is to apply a new multi-method approach to improve the understanding of landslide movements.

Methods: In this contribution, we analyzed a dataset of ground movements within the Italian Alpine region, including 21 landslides, 5 rock glaciers, and 1 slope creep. These movements differ in dynamics, exposure, slope, land cover, environmental triggering factors, and evolutionary behavior. We used ground displacement time series of InSAR data obtained from the c-band Sentinel-1 satellite, spanning the period from October 2014 to September 2021, with a revisit time of 6 days. The data, in the ascending and descending geometry, were processed with the SqueeSAR technique by TRE ALTAMIRA. We applied the Principal Component Analysis (PCA) on the temporal (T-mode) and spatial (S-mode) covariance matrix of the InSAR time series along the Line-Of-Sight (LOS) direction. Based on the analysis of the loading time series obtained from the T-mode, we were able to recognize the main trends and seasonal signals characterizing the InSAR time series. While from the S-mode we obtained the spatial patterns corresponding to each PC retained from the S-mode PCA and their temporal evolution. Then the ground displacement time series were grouped applying Hierarchical Clustering Analysis (HCA) to identify characteristic homogeneous deformation patterns based on the retained PC scores. Finally, wavelet tools were applied to the seasonal components separated from the InSAR time series and to the triggering factor time series, to detect localized non-stationary periodicities.

Results: The achieved results showed the capabilities of this approach to recognize a few characteristic ground displacement patterns that occur systematically in the InSAR time series, isolating landslides from the considered ground movements. This method allowed the description of the long-term behavior, seasonal periodicity and variations in the rate of displacement of the analyzed landslides. The weights and rankings of the separated components provided a footprint for the different ground movements, potentially revealing the phenomena based on the time series. Wavelet analysis allowed the interpretation of causal relationships between the seasonal signals and environmental triggering factors, showing correlations between landslide deformations and seasonal fluctuations.

Conclusions: In conclusion, interpreting the results from this multi-method approach, accounting for geological, hydrogeological, and environmental triggering factors, allows a deeper understanding and characterization of the alpine ground movements, overcoming the limitations of applying a single technique.

AUTOMATIC DETECTION OF LANDSLIDES FROM MULTI-TEMPORAL INSAR ANALYSIS

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Purpose: Over the last few years, the demand for ground deformation mapping and monitoring services at a large scale has increased in both public and commercial sectors. Interferometric Synthetic Aperture Radar (InSAR) data has proven to be the most cost-effective technology to meet users' requests. However, the large volume of data generated by InSAR presents challenges for end-users.

Methods: The SURFCLASS project, run by TRE Altamira and Politecnico di Milano, and funded by the European Space Agency (ESA) within the Future EO framework initiative, proposes a new methodology that leverages Artificial Intelligence (AI) to analyse and exploit InSAR displacement Time Series (TS). This approach classifies measurement points (MPs) and facilitates the analysis of displacement patterns related to driving deformation phenomena such as landslides, subsidence, and seasonal phenomena. SURFCLASS builds upon the previous ESA MATTCH project, involving the same partners, which developed a Machine Learning methodology (a Long Short-Term Memory network) to identify MPs with a change in their motion trend, acting as an early warning tool for end-users. This new methodology not only helps reduce data dimensionality but also provides a screening tool for end-users to analyse displacement patterns with greater ease. SURFCLASS is one of the first attempts to exploit InSAR TS analysis in combination with other contextual layers, such as SAR amplitude images, optical images, land-cover and land-use maps, and a digital elevation model of the terrain (Figure 1). Effective identification and categorization of deformation phenomena require the development of methods capable of capturing both spatial and temporal correlations that exist within InSAR datasets. The integration of additional modalities can further enhance discrimination power.

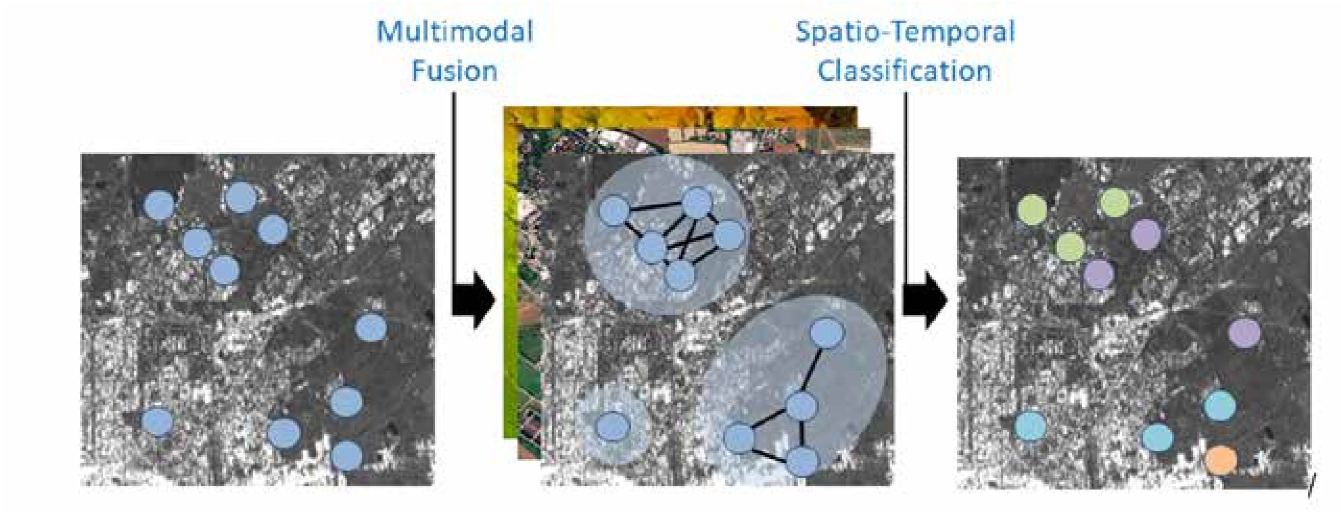

Fig. 1: Schematization of the multimodal spatio-temporal classification process

Results: The outcome of the project is an automatic algorithm that exploits temporal and spatial correlations among measurement points and SAR acquisitions to characterise ground deformation phenomena. Various Deep Learning methodologies are considered, including Convolutional Neural Networks and Graph Neural Networks, to extract spatial features from the resulting point clouds. Finally, a classification layer is designed to classify InSAR time series based on spatio-temporal features and additional information layers, enabling end-users to better understand driving phenomena.

Conclusions: The classification output generated by the SURFCLASS methodology is particularly valuable in responding to the pressing need for rapid and accurate landslide mapping, paving the way to automatic updates at regional and even national scales.

RELATIONSHIP BETWEEN CONDITIONING FACTORS AND THE RAINFALL INTENSITY NECESSARY FOR TRIGGERING SHALLOW LANDSLIDES IN PORTUGAL

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Purpose: The overall goal of this work is to create data-driven models to assess susceptibility to shallow landslides, and to understand how the conditioning factors influence in the triggering factor (rainfall) of shallow landslides.

Methods: Portugal mainland was selected as study area because it has an extensive database (Disaster) of landslides, and it still does not have a warning system for this type of hazard. Landslide occurrences were filtered in order to select only shallow landslides. For that, the historical daily rainfall data was collected automatically using Python from the Copernicus database. We used the rainfall duration and amount before the landslide to consider it a shallow landslide triggered by rainfall. A 30 m resolution DEM was used to extract the morphology of the terrains. The following condition factors were used in the analysis: lithology (1:1M), elevation, curvature, aspect, slope, land use, distance to river and distance to faults. The conditioning factors were selected using the algorithm Boruta in order to eliminate the factors considered irrelevant. The Random Forest algorithm was used for creating models for shallow landslide susceptibility and for analyzing the relation between conditioning factor and different rainfall threshold.

Results: Analyzing the collected rainfall data for each landslide occurrence, we notice that the rainfall events that triggered landslides in the northern part of Portugal contain higher intensity mean than the southern region. The Boruta algorithm showed that the land use, slope and elevation are the most important features for defining the susceptibility of landslides. For the relation between conditioning factors and rainfall intensity, the Boruta algorithm found that distance to rivers, slope and elevation are the most important features. The model for shallow landslide susceptibility using the Random Forest got an accuracy of 86% (feature importance: Land use > slope > elevation). The model for conditioning factors vs rainfall intensity got an accuracy of 77 % (feature importance: slope> elevation > lithology). If we ask for the Random Forest to differentiate the southern and northern parts of the country, taking in account the same extracted conditioning factors it gets an accuracy of 85 % (feature importance: lithology> slope > aspect).

Conclusions: It was evidenced that the northern part of Portugal contains shallow landslides triggered by higher mean intensity of rainfall events. The Boruta algorithm showed that the susceptibility for shallow landslide in Portugal is more linked to the land use, slope and elevation. The distance to rivers was also an important feature for predicting the rainfall intensity necessary to cause a landslide, which may be related to the proximity of the water table. All the models created obtained a satisfactory accuracy. The susceptibility model to shallow landslides can help stakeholders to make decisions on prevention of high susceptible areas, and all these models together can collaborate to the elaboration of a future warning system updated in near real time.

AI VS. HUMAN COGNITIVE ABILITIES: EVALUATING THE PERFORMANCE OF LANDSLIDE INVENTORIES IN HAZARD AND RISK SCENARIOS

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Purpose: Landslide inventories are essential for landslide susceptibility mapping, hazard modelling, and risk mitigation management. However, manual inventories have limitations such as subjective delineation of landslide borders due to the applied methodology, expert preferences, and available resources. To overcome these limitations, recent research has explored semi-automated and automatic mapping of landslide inventories using Artificial Intelligence (AI) techniques. The purpose of this study is to evaluate the usability of AI-generated and manual landslide inventories for hazard and risk scenarios under changing climatic conditions.

Methods: The study compared the accuracy and reliability of AI-generated and manual inventories in identifying and delineating landslide boundaries in different climatic scenarios. To assess the performance of the models, the study used F1-score, which is a measure of the balance between precision and recall in classification tasks. The study also evaluated the transferability of the models across different regions and climatic conditions.

Results: The study found that AI-generated landslide inventories showed promising results, but their usability for landslide hazard and risk studies remains a significant challenge, especially under changing climatic conditions. The models' performance in accurately delineating landslide boundaries and generating a ground truth representation after a landslide event ranged from 50-80% F1-score. The study also highlighted the need for accurate and reliable landslide inventories to assist in mitigating the risks of climate change-induced hazards and improve decision-making in disaster risk management.

Conclusions: The study concluded that evaluating the performance of AI-based models in accurately delineating landslide boundaries and generating a ground truth representation after a landslide event is critical for their successful application in hazard and risk scenarios. The study suggested the need for further research to test the models' transferability across different regions and climatic conditions to enhance their usability in hazard and risk scenarios. The study emphasized the importance of accurate and reliable landslide inventories in disaster risk management to mitigate the risks of climate change-induced hazards.

SESSION 3.5

ROCK FALLS AND ROCK AVALANCHES (part I)

GEOTECHNICAL SOLUTIONS FOR UNSTABLE ROR UNSTABLE ROCK MASS AT KUALA TEMOYONG, PULAU LANGKAWI, KEDAH

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Purpose: The stability of rock slopes is important and requires special attention as it involves public safety and disturbing the transportation system in the event of failure. Slope instability and failure occur due to geological factors such as weak slope material due to weathering as well as severe weather conditions, weaknesses in slope design and geometry, and geological discontinuities. This unstable rock mass is caused by an intersection between discontinuity plane orientations. The discontinuity is any separation in a rock mass having zero or low tensile strength. Based on stereonet kinematic analysis, it showed a potential of a wedge and planar failure.

Methods: Therefore, rock bolts and guniting have been selected as strengthening methods. Fourty (40) numbers of 6m long rock bolt with 2m spacing has been designed as a geotechnical approach to strengthening the rock slopes. Guniting along with weep holes are recommended on slope walls where there are water seepages

Results: The result achieve from Swedge Software shows that only one (1) number of 6m length passive rock bolt of with 60 tonne tensile strength is enough to cater the potential wedge failure identified from intersections between J1 – Bedding of the slope. Due to limitation of bar tensile strength, the designer re-designed the tensile strength of the rock bolt to 20 tonne/bolt with 2.0m spacing. All 40 nos of rock bolt with 2.0 m spacing were designed and installed to achieved Factor of Safety 1.5. The installation of rock bolt must be supervised by geologist as the vertical and horizontal angle is varies for each point. The geologist will correlate with the dip, dip direction and slope direction from rock assessment. The location of rock bolt proposed in the construction drawing is different from the exact location on site. The rock assessment conducted is on early 2021 meanwhile the design phase is on the end of the year 2021 thus the rock slope is already weathered. Thus, during the installation, the planar failure was newly found. Number of rock bolt that initially focused on only wedge failure is distributed also to the by the engineering geologist. The pull-out test of ten (10) numbers of rock bolt show that each bolt can achieve more than 1.5 times Working Load. This shows that the tested rock bolt is beyond the failure region of rock.

Conclusions: The design of the rock slope protection such as rock bolt is a complex design where the geotechnical engineer needs to understand the type of rock and collaborate with the engineering geologist in order to come out with the optimum detail design. The software needs to be cross-check with the calculation from the books and journal because the selection of rock bolt parameter plays crucial outcome of the design. The design of rock bolt needs to ensure the availability of the material on market. The tensile strength of the rock bolt needs to be reliable to prevent over design of rock slope protection.

QUANTIFYING UNCERTAINTY IN THREE-DIMENSIONAL ROCK SLOPE FAILURE

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The initiation of slope failures in fractured/jointed rock masses is governed by the kinematics of interaction between individual blocks of rock and by the interaction between the blocks within the mobilized rock mass once the failure commences. However, the internal deformations within the rock mass can only be observed externally at the rock slope face. An additional challenge is that the process of rock mass deformation is fundamentally stochastic, a function of the distribution of the joints and fractures, their orientations, and their persistence, among others. Herein we present an approach for incorporating this variability into rock slope stability analyses which allows objective identification of the most important characteristics influencing rock slope failure, and in the event of failure, the propagation of the sliding mass downslope. This analysis is achieved through a workflow that links an open-source implementation of the Discrete Element Method (DEM) with other open-source packages to perform the stochastic analysis as well as a global sensitivity analysis of slope failure and runout in a discontinuous rock mass. The realizations generated in this stochastic analysis describe the internal structure and the shape of individual rock blocks within the fractured rock mass. In this process we treat joint and fracture set properties such as strike, dip, and spacing, as random variables. Their distributions are defined by field measurements such that site-specific variability can be considered in quantifying uncertainty in rock slope response. Additionally, mechanical properties of the the rock mass are also treated as random variables such that the influence of geometric and mechanical properties can be considered simultaneously. The generated samples are assessed for stability using the three-dimensional DEM to evaluate the dynamic response of the rock mass for each of the realizations. DEM considers individual rock block geometry and the correct kinematic response is captured without any prior assumptions on the likely failure mode such that uncertainty in slope kinematic response due to natural variability in rock mass properties is automatically captured. The results allow the assessment of the relative contribution of the variability of each of these parameters, as well as variability due to the interactions between parameters. The insights gained from these analyses provide an objective assessment of the main contributors to the uncertainty of slope response and the potential consequences of slope failure.

EFFICIENCY OF KINEMATIC ANALYSIS IN DEMARCATING ROCKFALL SOURCE ZONE ALONG JOINTED ROCK SLOPE: THE CASE STUDY OF POGGIO BALDI NATURAL LAB, ITALY

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Purpose: The objective of this communication is to evaluate the effectiveness of using geometric stability analysis method to identify rockfall source area along scarps at slope scale. Moreover, we propose a practical approach, techniques, and algorithms for using photogrammetric and Terrestrial Laser Scanning (TLS) point clouds to determine the spatial kinematic susceptibility of a jointed rock slope.

Methods: The proposed methodology combines various techniques, including point clouds and Geographic Information System (GIS), to assess the spatial kinematic stability of a jointed rock slope surface at the Poggio Baldi natural laboratory (Italy). The study utilizes multi-temporal point clouds available at the Poggio Baldi landslide monitoring site to evaluate the failure susceptibility determined using semi-automatically extracted discontinuities. Additionally, the study quantitatively compares the suitability of discontinuities derived from TLS, Unmanned Aerial Vehicle (UAV) photogrammetric and hybrid point clouds for this analysis. The study also evaluates the results of the kinematic susceptibility analyses by comparing it with actual rockfall events detected through change detection analysis that occurred in recent years. Confusion matrices and performance metrics, such as accuracy, precision, recall, and specificity, were used to evaluate the results. Finally, the effect of overhanging blocks in the rock scarp on the occurrence of small block failures has been assessed. The results of this site-specific case study are discussed against a regional kinematic analysis to demonstrate the scale dependent bias of the kinematic analysis.

Results: The confusion matrices and performance metrics of the resulting kinematic susceptibility maps indicate that there are significant number of false negative (FN) and false positive pixels (FP). FN pixels suggests that actual failures were not simply explained by kinematic feasibility and FP pixels suggests the analysis underestimated stability conditions. These results imply that kinematic susceptibility alone cannot explain the failure phenomena in many cases. The study found that most pixels with higher susceptibility values were prone to planar failure, while overall, most pixels were prone to wedge failure. Moreover, the wedge failure predictions were found to be in better compliance with the ground observations, followed by planar and topple failures. The investigation of the pixel resolution influence on kinematic susceptibility prediction showed that a topographic pixel size of 3m and joint pixel resolution of 3m provided the best results for kinematic analysis. The study found that discontinuities derived from TLS point clouds provided the best accuracy, precision, and specificity, making it the best option overall.

Conclusion: The study findings suggest that the GIS-based modified kinematic method is a promising technique for assessing the failure susceptibility of rock cliffs using discontinuities derived from point clouds. However, the analysis showed that kinematic method could not be efficient enough in assessing failure potential in the specific morpho-geostructural setting at Poggio Baldi. Further improvements are necessary to enhance the performance of the commonly used Markland's method for slope scale assessments. The study results also suggest that TLS point clouds perform better than UAV photogrammetric and hybrid point clouds for assessing unstable zones.

INVESTIGATION OF PREDISPOSING FACTORS FOR ROCK SLOPE FAILURE IN SLOVENIA

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Purpose: Climate change has significant impacts on alpine and montane environments, with changes in temperature, precipitation, snow patterns, and freeze-thaw dynamics directly affecting rockfall intensity. In Slovenia, slope morphology, unfavorable geological and tectonic conditions, and climatic diversity contribute significantly to the large rockfall potential. In this research, we focus on studying the predisposing factors for rock slope failure based on temperature variations and geomechanical properties in carbonate, metamorphic, and igneous rocks.

Methods: At the four study sites in the Alpine foothills, which are characterized by different geological and geomechanical properties of the rock and different thermal conductivity of the material, multi-method monitoring has been carried out for two and a half years now, including measurements of temperature and stress in the rock at three depth levels. The geotechnical sensors are wired using LoRa communication protocol and a LoRa gateway and are powered by a base station that also serves as an in situ data logger.

Results: We present the preliminary results of the analysis of such rock faces and the effects of temperature and stress variations on rock deformation at the surface and below the surface. Each individual rock type has different engineering and geomechanical properties and predisposing factors that can affect exfoliation, discontinuity formation, and fractures. The comparison of correlation between temperature and stress at different rock depths from the field is consistent with measurements from laboratory tests.

Conclusions: The results of in situ temperature and stress monitoring and laboratory analyzes showed comparable rock fracturing conditions. Therefore, based on the applied approach, we can define important predisposing factors in different geological environments that affect rock fracturing.

This project is funded by the Slovenian research Agency, the project title: Deciphering the sensitivity of rock faces to climatic changes and freeze-thaw cycles in permafrost-free regions (J1-3024).

COMPARISON BETWEEN METHODS FOR ASSESSING BLOCK VOLUME AND SHAPE DISTRIBUTIONS

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Purpose: This contribution aims at showing the existence of a relation between the volume of a rock block within a rock mass, and its shape. In the past, some authors (Kalenchuck et al., 2006) pointed out that the larger the blocks, the more likely it is that their shape is equidimensional. This fact has been investigated by creating a synthetic In-situ Block Size Distribution (IBSD) and the corresponding Shape Distribution (SD). In addition, both a Discrete Fracture Network (DFN) and an analytical model (Umili et al., under review) were employed to generate the IBSD based on orientation and spacing data, in order to assess the coherence of their results.

Methods: A synthetic rock mass was modelled employing a DFN software, featuring three perpendicular joint sets, each characterized by a spacing distribution. From this model, vertexes and volume of each simulated block were obtained, on the basis of which the IBSD and the SD were built. IBSD represents a relation between each possible value of the block volume and its probability of not being exceeded. SD relies on the method proposed by Palmstrøm (2001): based on the ratio Lo/Sh of its longest (Lo), and shortest (Sh) sides, and the ratio In/Sh of its intermediate side (In) and Sh, each block is classified as equidimensional (E), rod (R), blade (B) or slab (S) and plotted on a logarithmic shape chart. The method described in Umili et al. (under review) was used to produce the analytical ISBD and the corresponding SD based on the same data input in the DFN.

Results: Figure 1 compares the IBSDs built using the DFN and the analytical method, showing a good agreement of the curves. Figures 2 and 3 show the SD built using the two methods. The four shape categories are classified based on volume classes through histograms to compare the distributions of the different shapes and appreciate the similarity of the results of the two methods. Similarly, the results were plotted on Palmstrøm's shape chart.

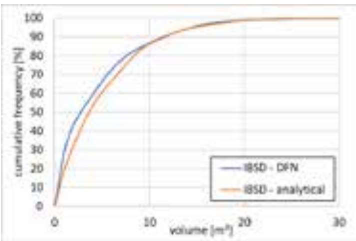

Fig. 1. Comparison of the IBSD built using DFN and analytical method.

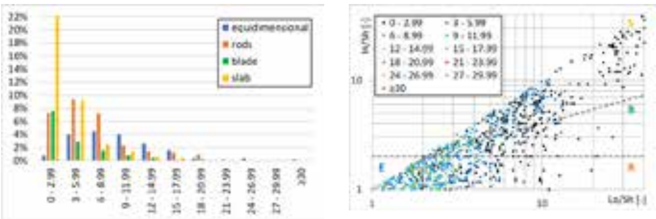

Fig. 2. SD built using DFN represented through left) histograms, right) Palmstrøm's shape chart.

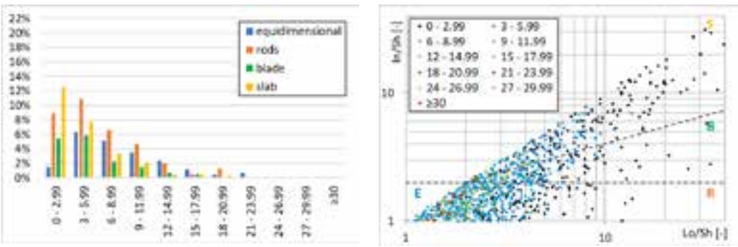

Fig. 3. SD built using the analytical method represented through left) histograms, right) Palmstrøm's shape chart.

Conclusions: This study, although based on a simple and synthetic case study, confirms that the DFN and the analytical approaches produce similar results in terms of IBSD and SD. Moreover, it seems to support the existence of some relations between block size and shape, as equidimensional blocks become dominant for larger volumes.

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FACTORS INFLUENCING THE DEPTH OF UNDERCUTTING OF FLYSCH BEDS IN THE COASTAL CLIFFS OF SLOVENIA AND THE RESULTING ROCKFALL

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Purpose: The Slovenian coast is characterized by flysch - intercalations of thin-bedded (generally several centimeters thick) hard sandstones and soft marlstones with occasional calciturbidite layers up to 9 meters thick. Because of this heterogeneity and the factors that cause the erosion and disintegration of the rocks (abrasion by the sea and waves, precipitation, freeze-thaw cycles, temperature differences, wind, etc.), the erosion of the coastal cliffs occurs quite rapidly. One of the most pronounced erosion processes is the undercutting of the harder sandstone and calciturbidite layers, from which numerous blocks fall out of the slope. These blocks are the source of rockfalls and, given the great height of the cliffs (up to several tens of meters), pose a great danger to bathers and visitors of the coastal areas. The blocks are mainly defined by two fracture sets (R1 and R2) and the thickness of the layers. The objective of our research is to investigate the undercutting depth and its correlation with various engineering geological, geotechnical, and mineralogical parameters of the rocks. We measured these parameters at 27 sites along the Slovenian coast.

Methods: Several field measurements were performed: the orientation of the R1 and R2 fractures and their spacings, the thicknesses of the sandstone, calciturbidite layers, and the underlying marlstone layers, the uniaxial compressive strength determined with the Schmidt hammer, the orientation of the beds and the slope, and the depth of undercutting beneath the sandstone/calciturbidite layer. In the laboratory, we determined the mineralogical composition of the rocks, and several geomechanical tests (tensile test, uniaxial compression test, and large direct shear test) are in progress. After the shear tests, the samples were scanned with an optical scanner to determine their failure rate.

Results: Preliminary results show a very good correlation between the depth of undercutting and the spacing of R2 fractures, as well as with the thickness of the sandstone/calciturbidite layers. As expected, the correlations between layer thickness and fracture spacing are also good for both fracture sets. Somewhat unexpected is the good correlation between the depth of undercutting and the spacing of the R2 fracture set, but not with the spacing of the R1 fracture set. This could be influenced by the shoreline orientation, and the inclusion of this factor is still a work in progress. Mineralogical composition shows a good correlation of undercut depth with quartz content in the sandstones (which can be explained by higher cementation) and a correlation of undercut depth with clinochlore content. Based on calculations using the RocScience Dips program, the possibility of planar and wedge-shaped slip is minimal. Numerical modeling of stability shows that tensile strength plays the decisive role for the stability of the cliffs.

Conclusions: The depth of undercutting is correlated with some measured factors, and we are still making measurements to better understand the processes of undercutting harder rocks as the research project is ongoing. The authors acknowledge that project J1-2477 "Erosional processes on coastal flysch cliffs and their risk assessment" was financially supported by the Slovenian Research Agency.

FALLS, SLIDES AND AVALANCHES: A BACK-ANALYSIS OF LANDSLIDE EVENTS TO DIFFERENTIATE BETWEEN MOVEMENT TYPES

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Purpose: Landslides can be devastating events, and predicting their runout is a key element in mitigating their impact. They can be divided into several types according to material type and mass movement, which entail quite different runout processes. While falls refer to movements of individual blocks falling and bouncing down slopes, slides and avalanches involve more fluid movements of the mass down the hillsides. However, individual landslide modelling requires distinguishing these types of runout. Indeed, these three types of mass movement cannot be adequately modelled by the same means, but judging which event in a series of apparently similar landslides is a fall or a slide is difficult. One hypothesis postulates that the volume of eroded material is a good predictor of the type of movement, and that there is a volume boundary between fall, slide and avalanche. However, this threshold is poorly constrained, ranging from 104m3 to 106m3, which can have a strong impact on runout model predictions for medium-sized landslides.

Methods: In this study, we model a set of landslides triggered by the 2016 Kaikoura earthquake (Bernard et al., 2021) using two different approaches: the first, a shallow water equation approach, using Gerris combined with a Voellmy rheology (Hergarten & Robl, 2015), is particularly suitable for sliding movements, and the second, HyLands (Campforts et al., 2020), an empirical topographic approach, is appropriate for landslide and fall modeling. Based on these two simulation methods, we perform a landslide back-analysis to determine the transition between fall and slide behavior in our events.

Results: We find that the shallow water equation approach is more suitable for modelling large landslides, while the HyLands approach shows better results for small landslides. The transition between the two approaches is gradual and occurs around a source volume of 104 m3 in our dataset.

Conclusions: The transition from rockfall to rock avalanche behaviour appears to be gradual and indeed volume dependent. Knowing the relationship between source volume and runout type opens up possibilities for statistical prediction of the runout length as a function of volume.

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EFFECTS OF GRAIN DIAMETER ON RAPID SLIDING OF DEBRIS FLOWS

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Purpose: A continuum model to predict the mobility of landslides is developed according to the formulation by Savage and Hutter as well as the main 'microscopic aspects' affecting the rapid sliding of granular masses. Specifically, a 'frictional–collisional' rheological law allowing to simulate the energy dissipation related to grain inelastic collisions and friction, simultaneously acting within the basal 'shear layer', is proposed and applied.

Proposed model: Following the 'continuum mechanics approach' applied to rapid granular flows, according to which the flowing mixture of solid particles and water is described as a single-phase, incompressible and homogeneous material, the Savage and Hutter (SH) formulation is considered and improved. The original mass balance and x-momentum balance (one-dimensional) equations are rewritten by taking into account the effects of the pore-water pressures, the mass variation due to erosion or deposition processes as well as the typical (frictional–collisional) mechanical behaviour of a granular flow, expressed as:

$$\tau \cdot dx = -sgn(v) \cdot \left(\bar{r} \cdot \tau_{fr} + r \cdot \tau_{disp}\right) \cdot dx$$

T_{fr} is the shear stress associated with the frictional regime; T_{disp} is the shear stress associated with the collisional regime and depends on *dp* (grain diameter); *r* and $\bar{r}$ (defined as 1 - r), dependent on the flow velocity *v*, allow a "weighted" balance of the shear resultant force between the frictional and dispersive stresses, statistically acting along the sliding surface (Federico & Cesali, 2015).

The governing mass balance and x-momentum balance equations are rewritten as:

$$\frac{\partial H}{\partial t} + \frac{\partial}{\partial x}(v \cdot H) - \varepsilon(v) = 0$$

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} = gsin\theta - sgn(v) \cdot \left\{\bar{r} \cdot \left[(1 - R_u) \cdot (gcos\theta) + \left(p_{disp}/\rho H\right)\right]tan\delta + r \cdot \left(\tau_{disp}/\rho H\right)\right\} - \left[(1 - R_u\, d_w)K_{act,pas} + R_u \cdot d_w\right] \cdot (gcos\theta)\frac{\partial H}{\partial x}$$

H being the thickness of the flowing granular mass; *ε(v)*, the erosion/deposition rate; *θ* the slope of the sliding surface; *Ru*, the interstitial pressure coefficient; g, the gravity acceleration; ρ_{disp}, the normal to boundary of the collisional stresses; *ρ*, the density of the debris flow; *δ*, the basal friction angle; d_w, the depth of the free surface; $K_{act,pas}$, the active/passive earth pressure coefficient.

Results: The large scale test performed at the USGS on May 20-22, 1997 (Iverson et al. 2016) is considered (Figure 1d). At the head of the flume, a mixture of sand (*dp* ϵ [0.0625 ÷ 2] mm; 33%), gravel (*dp* ϵ[2 ÷ 32] mm; 66%) and water (total volume, 10 m^3) is located. Along the channel, at sections I, II and III, sensors and transducers measure flow depth. The experiment is simulated through the proposed model (*dw* = 1; *δ* =28°; *ε* = 0; *θ* = 31°).

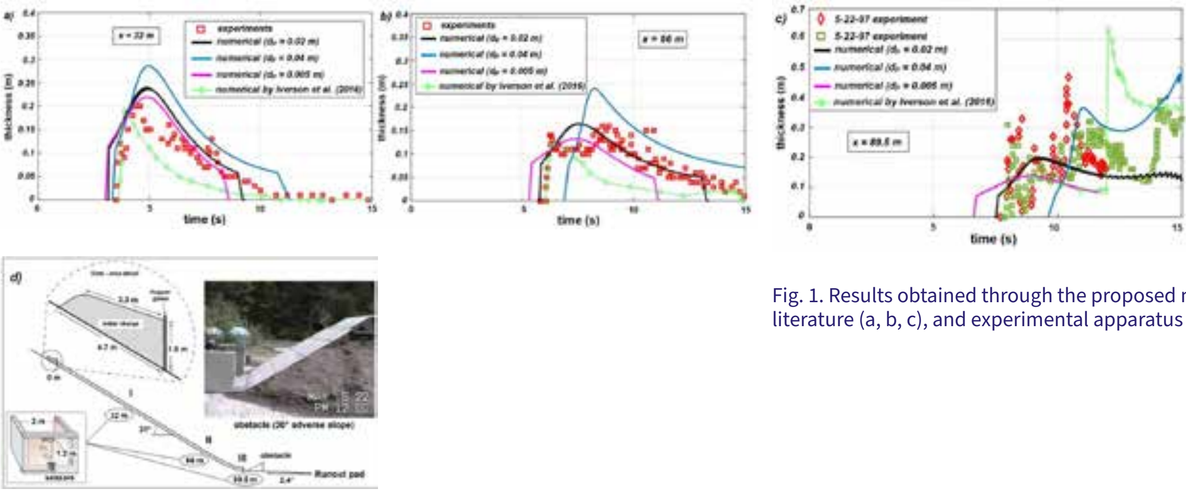

Fig. 1. Results obtained through the proposed model and from literature (a, b, c), and experimental apparatus (d).

Conclusions: An appreciable agreement is observed with reference to the thickness values, measured and computed for *dp* = 0.02 m. For *dp* ≤ 0.005 m, the energy dissipation associated with collisional regime is not significant, a mainly frictional regime thus occurs and the measured flow depth profiles are not correctly simulated.

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DATING OF THE DEPOSITS OF ROCK AVALANCHES IN THE CONTEXT OF THE CLIMATE CHANGE IN THE DRY MOUNTAIN REGION, PAMIRO-ALAY MTS., TAJIKISTAN

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Purpose: The occurrence of landslides, rock avalanches, and debris flows is strictly connected to precipitation. Different rainfall values (for example, 1-day, 3-day, or 5-hour rainfall) are discussed as the most valuable data for mass movements modelling, and are treated as the main triggering factor. The presence of rock avalanche deposits in a dry climate, where rainfall is very low, suggests that their origin is related to other precipitation values than those noted nowadays. An attempt of dating of these deposits can show the scale of climate change in the area. The scale can range from the possibility of landslides and rock avalanches on the one end, to the dry, contemporary climate, with only rock falls noted to the other.

Methods: The Schmidt hammer rebound value, the lichenometric data and cores from Juniperus sp. trees were collected during field research. The Schmidt hammer R-values were compared with the data collected from glacial moraines. The size of Xantoria sp. lichens thalli were compared to lichen's growth curve from Tien Shan. The Juniperus sp. tree rings were calculated by botanists dendrochronometry laboratory. All the collected data were compared to paleo-climate reconstructions from this region.

Results: On the basis of rebound values one can note that the relative age of rock avalanche deposits is significantly lower than that of the youngest moraines. The data have proven that deposits cannot be connected with the end of the Pleistocene. The comparison of Xantoria elegans thalli size with the data from moraine boulders also confirms that rock avalanches are much younger, as the reference of their average size with growth curves suggests the age can be estimated at around 250-350 year of thalli. The Juniperus sp. tree ring samples have given the oldest age of 352 years. Three rock avalanches mapped in two valleys are of a very similar age. Such dating suggests that they were formed during the same climate period. The paleo-climatological research from this region delivers precise data. The humid period of LIA in Central Asia is dated between 1550-1910. The highest precipitation during that time was recorded at the beginning of the second half of 17th century (1660-1680). The dendrochronological data suggest that 1670 was the beginning of growth of the oldest tree on the investigated deposits, which means they had to be formed at that time. The lichens thalli size also suggest the age of deposits of about 300 years.

Conclusions: Similar rebound values of three rock avalanche deposits prove that they were formed at the same time. The tree ring samples and the lichen's thalli indicate the age of deposits of about 350 years. This dating corresponds with paleo-climate data for the most humid period during LIA in the Pamiro-Alay. These premises suggest that rock avalanche deposits may potentially serve as climate indicators in dry mountain regions.

RECONSTRUCTION OF A LARGE-SCALE COMPOSITE LANDSLIDE AND DEBRIS FLOW HAZARD - A CASE STUDY OF LUANSHIBAO

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Purpose: In this study, a hypothesis was put forward based on previous studies and satellite images on the cause and movement process of the riprap landslide. The main purpose of the study was to analyze the impact range of the landslide/debris flow through 3D numerical simulation and compare it with the current situation.

Methods: Collect the relevant data of the study area to understand its geological background and the scope of the collapse. Digital terrain and parameters are required by the program into Flow-R, Rockyfor3D, LS-RAPID, and RAMMS to analyze the impact range of the collapse. The cause of landslides in chaotic rocks is complex. This study attempts to analyze it from different aspects through several numerical simulation software – Flow-R, Rockyfor3D, LS-RAPID, RAMMS. Compare the simulation results with the current situation to find the most suitable parameters, analyze the sliding length and area, and compare the applicability of the software in the research area and the rationality of the proposed assumptions.

Results: LS Rapid uses the input of seismic acceleration to obtain the hypothetical collapse situation and movement process in the time series. The simulation results are shown in Figure 1. The final results of this simulation are roughly consistent with the field investigation results.

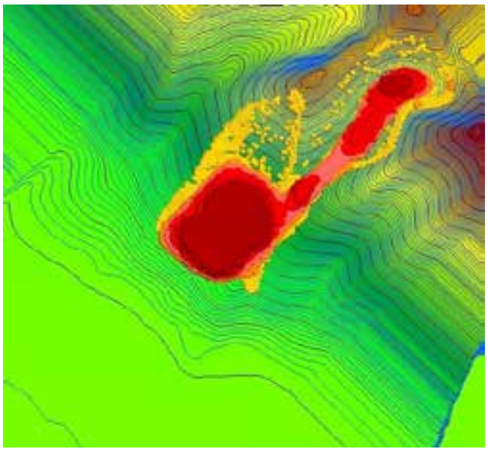

Fig. 1: Seismic simulation results from LS Rapid.

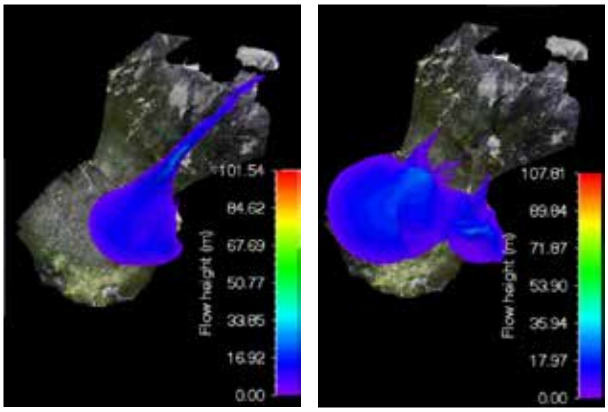

Fig. 2: RAMMS simulation results with different sources.

From the satellite images, it can be seen that about two-thirds of the sliding position is covered by traces of landslides. The simulation results are shown in Figure 2. The simulation process of RAMMS will not erode the terrain. From the soil accumulation map, it can be seen that the collapsed soil of source 1 is along the backfilled mountain and The junction below the ravine slipped. There was no situation where the ridgeline on the right side of the mountain was washed away and the entrained slope toe soil was destroyed.

Conclusions: In terms of simulation efficiency and practicability, Flow-R has the shortest simulation time. It analyzes the impact range of collapse in a simple and fast way. The program is designed to simulate all possible ranges, so the simulation range is overestimated compared with the current collapse range. Rockyfor3D may be due to a large number of simulation times The simulation results cannot cover the research area. It may not be suitable for large-scale collapse impact assessment. The simulation results are the number of times each grid passes through the material source. LS-RAPID simulated soil The large difference in the time of stabilization is related to the set parameters. Although the simulated influence range does not reach the actual collapse range, the overall simulation can restore the collapse process. RAMMS simulation time is short, The movement and accumulation process of the material source can be seen. The influence range and accumulation depth of the simulation results are roughly consistent with the actual collapse range.

SESSION 4.1

REGIONAL AND GLOBAL LANDSLIDE INVENTORIES: PARAMETERS AND PRINCIPLES OF COMPILATION

A LANDSLIDE DATA BASE MODEL FOR CLIRTHEROADS PROJECT IN SERBIA

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Within the project Mainstreaming Climate Resilience in the Road Transportation Management in Serbia (CliRtheRoads), a complex software solution was developed to support Public Enterprise Roads of Serbia in climate change adaptation planning and management. The software solution comprises 1) web portal for data entry and management for authorised users 2) publicly available web GIS part 3) mobile GIS application and 4) back-end database (Figure 1).

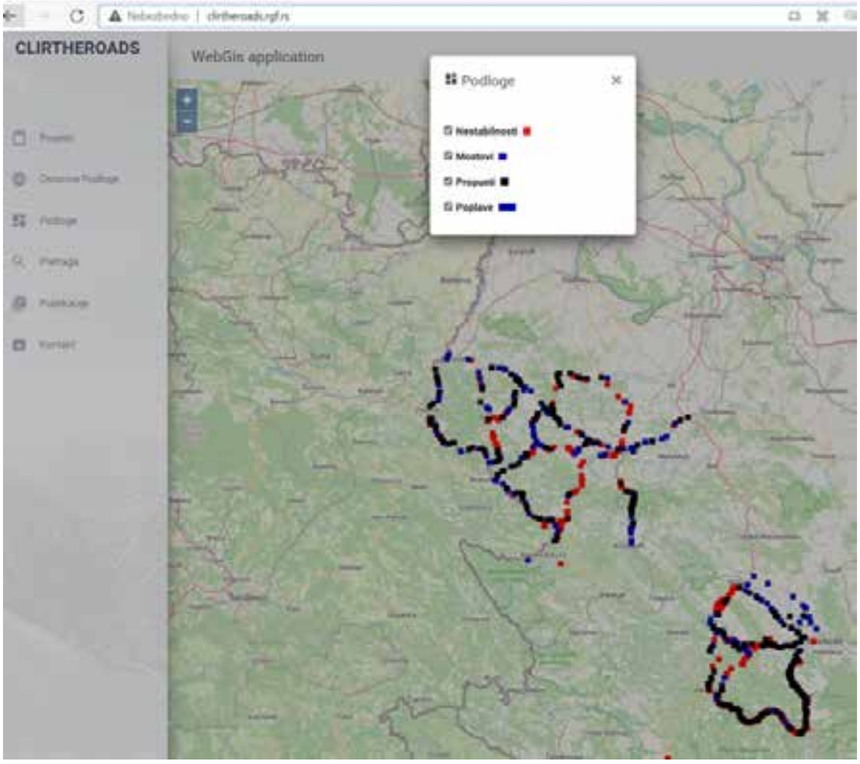

Fig. 1: Screen shot of publicly available web GIS with field tours on the two test areas (in Serbia).

In order to store and process the data collected during field visits and surveys, the data base developed in project first phase (Valjevo test area), was modified to include new datasets and to store new datatypes (as floods), and new modules (as activity cost) for Kraljevo test area. Both test areas have been chosen due theirs diversified characteristics, many climate related hazards, and the fact they suffered greatly from disasters recently (Abolmasov et al. 2017, Abolmasov et al. 2021). The database was upgraded to new model aimed for maintaining legacy data from both test areas, but also for future infrastructure resilience projects based on same approach, to enable that all data will be stored and mapped in a unified manner. The data model include 1) main concepts (entity types) for the instabilities, with detailed data comprising common and specific attributes, 2) storage of multimedia (mainly photo from field work, but possible video as well), 3) knowledge base with cost of activities, including catalogue per each entity type with job type and description, unit and total price, maintenance type (regular maintenance, rehabilitation, urgent maintenance), including recommending activities (system allow user to add specific activities, description and cost that is further calculated and aggregated with other data); 4) secondary data from other sources (other projects, legacy data and external resources), or from interpreted data. The data was stored in the PostgreSQL Database, a web application was developed (using PHP) to facilitate data input, maintain knowledge database and calculate cost of recommended activities. There is a total of 461 records with fully described instabilities (slides, falls, topples, flows), documented by large number of photographs from the field. Additionally, every record is supplemented by engineering solution to support field engineers or decision makers for better road management in climate changing conditions.

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COMPILATION OF A GEOMORPHOLOGY-BASED LANDSLIDE INVENTORY FOR EASTERN MACEDONIA AND THRACE REGION, GREECE

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Purpose: Landslide occurrence is widespread and common over the continental and island parts of Greece. Most regional studies of landslides and landslide hazard rely solely on reports of historical and recent landslide locations and locally focused inventories. Northern Greece, and more specifically Eastern Macedonia and Thrace region, has a low frequency of reported landslides, but nevertheless with significant hazard risk and risk for the local communities and infrastructure. The lack of a detailed landslide dataset (rainfall- and/or earthquake-induced landslides) over the region, led us to the creation of a new geomorphology-based landslide inventory for the region of Eastern Macedonia and Thrace (including Thasos and Samothrace islands). A concise regional landslide inventory should include landslide polygons and linear features traced in as much detail as possible, for both active/recent landslides and inactive/prehistoric landslides.

Methods: The creation of the landslide inventory for Eastern Macedonia and Thrace region was based on a geomorphological approach, using detailed digital elevation models, supplemented by remote sensing data. Landslide mapping was performed manually, using as baseline a detailed digital surface model (DSM) with 5m resolution, provided by Hellenic Cadastre. Landslide polygons and scarp features were traced over the DSM by using key morphological features identified in relief and slope maps. Mapped landslide features were then checked using aerial and satellite imagery, in order to check validity and relative age of activity. Supporting data, such as reported landslide occurrences and satellite-derivered displacement time-series from European Ground Motion Service (EGMS) were also used to identify activity of the mapped landslide polygons.

Results: More than 13,000 landslide polygons were mapped in the 14,000 km2 area covering the region of Eastern Macedonia and Thrace (Figure 1). Mapped landslides were mostly deep-seated landslides, rockslides and earthflows with a significant size (from ~30m up to 1-2 km). The inventory did not include individual rockfalls and debris flows.

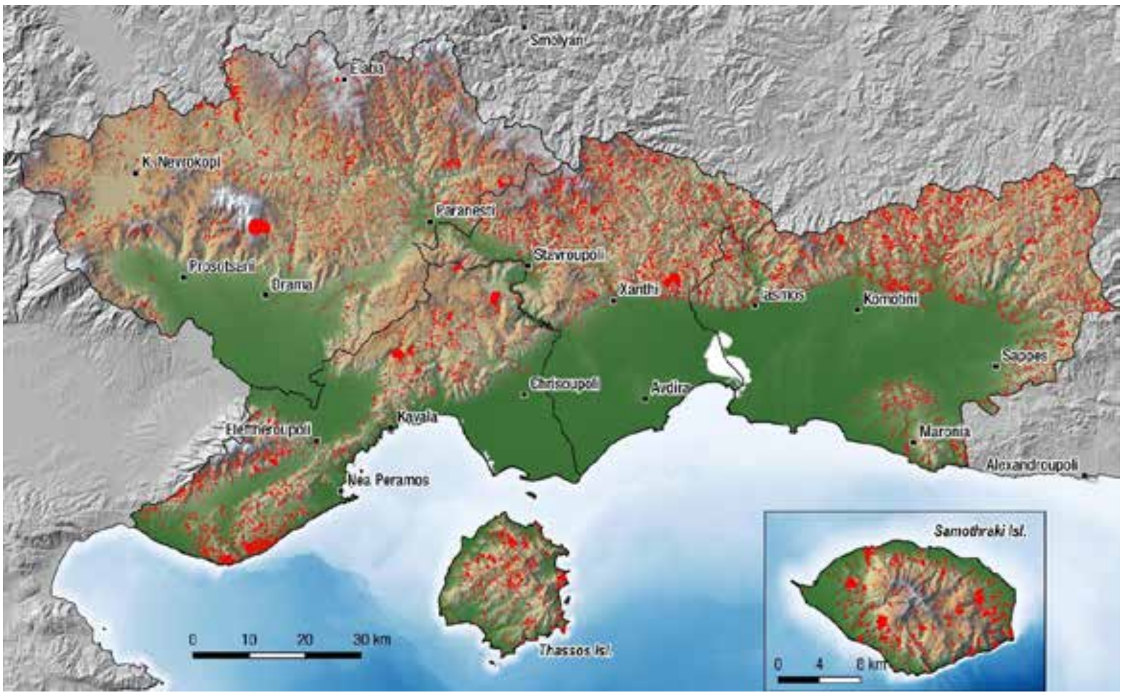

Fig. 1: Compiled inventory of active/recent and prehistoric landslides (red polygons) in Eastern Macedonia and Thrace region of Greece.

Conclusions: This new detailed inventory of 13,000+ active and prehistoric landslides for the Eastern Macedonia and Thrace region can provide the basis for creating inventory-based susceptibility and hazard maps for rainfall- and earthquake-induced landslides in the region. We plan to expand the current landslide inventory by acquiring more detailed digital surface models in local and regional scale. Landslide polygons can also guide the future creation of detailed landslide maps in local scale. Using the new detailed inventory, we plan to examine exposure and vulnerability of critical infrastructure (built-up areas, critical facilities, major road networks etc.) in Eastern Macedonia and Thrace in order to assess the risk from landslides. We acknowledge support of this work by the project “Risk and Resilience Assessment Center – Prefecture of East Macedonia and Thrace -Greece.” (MIS 5047293) which is implemented under the Action “Reinforcement of the Research and Innovation Infrastructure”, funded by the Operational Programme "Competitiveness, Entrepreneurship and Innovation" (NSRF 2014-2020) and co-financed by Greece and the European Union (European Regional Development Fund).

NATIONAL LANDSLIDE DATABASE OF THE HELLENIC TERRITORY: AN EFFECTIVE TOOL FOR LANDSLIDE HAZARD MANAGEMENT

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Purpose: Landslides constitute one of the most important natural disaster in Greece, showing widespread manifestation and causing considerable damage and fatalities every year. The Hellenic Survey of Geology & Mineral Exploration (HSGME) representing the National Geological Survey of Greece, officiates as the geoscientific adviser of the government and keeps an up-to-date file of about 3000 engineering geology reports on the study of landslide phenomena. It refers to the Hellenic Territory from the half of the last century till today and integrates constantly the recent events. The Engineering Geology Division of HSGME has formed a Landslide Research Team which directly revises the suffered site after a landslide occurrence and composes a report including the event's characteristics (place, time, dimensions etc), the causes and the triggering factor, as well as the implications.

Methods: A large number of the information recorded in these technical reports are digitally stored into a Geographical Information System (GIS) as geo-database. This relational database management system summarized over 5000 landslide records with a unique identification number to each studied landslide event attached to information concerning the evolution of the phenomenon, date of manifestation, type of movement, geometry, state and type of activity, triggering factor, causes, consequences, proposed remedial measures and the degree of their compliance. Moreover, information concerning the manifestation's location is filled in the database, such as geographic and administrative specification, dip slope, land use, erosion, geotectonic zone, geological setting, lithological composition, inclination of strata, thickness of weathered zone, seismic risk zone and more.

Results: The current paper, contains the results of GEOKA research project launched in 2018, conducted in the framework of the Operational Program "Competitiveness, Entrepreneurship and Innovation" (Project: "Studies and researches support to the energy sector, industry and entrepreneurship", Sub-Project: "Susceptibility assessment of landslides in the Greek territory - Volcanic study and risk assessment") financed by the European Regional Development Fund. Objective of GEOKA was to update the existing landslide database by adding records, matching the landslides data with European and International standards and increasing data accuracy and integration by field survey in reactivated landslides. Result of the above is a revised inventory map of the occurred landslides in national scale, that taking into account the spatial distribution of landslides can be used for the production of a landslide density map and moreover susceptibility maps in regional and national scale can be conducted as a result of the analysis between the spatial distribution of the landslides and a group of causative factors (geological, topographical, hydrological characteristics of the area and more).

Conclusions: GEOKA aims to better understanding the landslide-hazard in Greece that contributes to increase the safety of vital technical works, reduce the constructions' cost, manage land use planning and decrease the vulnerability of people and goods.

TOWARDS A SYSTEMATIC UPDATE OF THE CYPRUS LANDSLIDE INVENTORY USING COPERNICUS SATELLITE DATA

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Purpose: Cyprus is in the Mediterranean fault, where a unique geodynamic regime exists due to interaction between the Eurasian and African plates. This leads to landslides, particularly in areas of steep topography, posing significant impacts to the built environment. Large landslides occur in the western part of Cyprus (Paphos District), due to the presence of landslide-prone geological formations. Between 2008-2010, the Geological Survey Department (GSD) and Scott Wilson Group conducted the "Paphos Landslide Study", to evaluate landslide susceptibility, hazard, and risk in Paphos District, developing a landslide inventory. Although the GSD systematically updates this inventory using inclinometers and extensive field investigations, this is only performed for areas with ground stability issues, leading to inadequate landslide documentation.

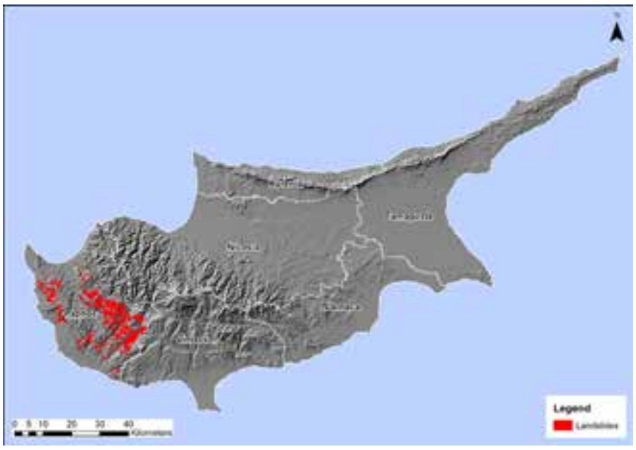

Fig. 1: Cyprus landslide inventory map (GSD) - Digitised map based on data obtained from the Geological Survey Department.

Moreover, data unavailability and the lengthy process for reliable dataset production reduce the field investigation feasibility that require quick action. Additionally, these costly methods provide limited spatial coverage, a particularly problematic characteristic for extensively damaged areas. Nevertheless, the Sentinel-1 sensors with their temporal and spatial characteristics can be utilized to rapidly detect landscape changes due to landslides, regardless of inaccessibility or adverse weather conditions, and their free distribution provides a cost-effective opportunity for systematic landslide monitoring.

Methods: A time series analysis of ascending and descending Sentinel-1 datasets was conducted for the period 2016-2022 using Permanent Scatterers techniques and Coherent Change Detection (CCD) over Cyprus. Different look angles and slope directions were also considered. Several landslides detected via multi-temporal Interferometric Synthetic Aperture Radar (InSAR) techniques, were matched with areas mapped by the GSD. Moreover, a CCD analysis was performed calculating the Coherence Difference and the Normalized Coherence Difference (NCD) indices in each image pair. Consequently, pixels with high probability in landslide occurrence were identified using CCD and correlated with Persistent Scatterers that indicated a degree of displacements. The final deformation maps were then validated using the GSD landslide inventory.

Results: CCD provide qualitative information on landslide occurrence, showing the extents of the landslide-affected areas through exploitation of the multi-pass advantages of the Copernicus Sentinel-1 mission, combining numerous pre-event and co-event SAR images. Detection accuracy improved when NCD index was used, with a noticeable increase in the probability of correctly detecting landslides. Concurrently, Persistent Scatterer Interferometry (PSI) identified specific points and clusters where ground displacement occurred, providing quantifiable information. InSAR time-series analysis revealed several deforming sites in the wider Paphos District, with a maximum mean deformation rate of -10mm/y for the investigated time-period.

Conclusions: The application of interferometric stacking methods through the proposed integrated CCD-PSI methodology facilitated studying the landslide occurrence and validating the methodology through correlation with the GSD landslide inventory. Results of both SAR analyses were integrated in a common framework to create a tool for systematic monitoring of ground displacements in the broader region of Paphos. Integrated results from the two methodologies can be used to continuously update the landslide inventory and provide directions to responsible authorities for carrying out new site-specific investigations.

TOWARDS A NATIONAL OVERVIEW FOR ROCK AVALANCHE POTENTIAL

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Several rock avalanches with significant consequences have taken place in Norway during the last centuries, leading to high societal awareness with respect to potential future occurrences of this natural hazard type. Consequently, a program of mapping unstable slopes across Norway was initiated in 2006 and several high-risk sites have now been investigated in detail and are monitored continuously. So far five out of eleven Norwegian counties have been analysed systematically for unstable rock slopes. Identified unstable slopes are assessed using a hazard and risk classification system established in 2012 (Hermanns et. al. 2012). This process is time intensive, and ongoing mapping activities might not be focused on the objects that need most urgent follow up. Furthermore, national susceptibility maps exist for all other landslide processes in Norway. Those are important for land-use planning and decision making for building projects. However, it is impossible to produce susceptibility maps for potential large rock slope failures, as we cannot capture those that do not show clear signs of gravitational deformation yet. The lack of a national overview of potential hazard posed by unstable rock slopes and the long time between the detection of an unstable rock and its final classification have caused difficulties for larger building projects especially when critical infrastructure is involved.

To establish a complete national overview of potential large rock slope failures and their hazard and consequence potential, a national overview mapping project has been started by the Geological Survey of Norway. This will achieve better prioritization of objects with higher risk for detailed assessment than the current county-by-county approach. The project is divided into several steps: (1) systematic analysis of remote sensing data (e.g. detailed DEM, orthophoto and InSAR data) to locate potential unstable rock slopes; (2) a simplified ranking with respect to failure likelihood; (3) assessment of potential consequences.

To minimize the area and time required to complete Step 1, presently known unstable rock slopes have been analysed with respect to different criteria. Results indicate that the study area can be restricted based on available relief, presence of inhabitants and distance to the shorelines (fjords and lakes) down to roughly one third of the total land area of Norway. With respect to Step2, we use a simplified ranking that is primarily based on signs of activity and visible stage of development. Step 3 involves an automated volume estimation, semi-automated run-out assessment, and an empirical displacement wave run-up height assessment, all optimized to be conducted on a large number of unstable rock slopes (~700). Based on a combination of expected consequences and the relative ranking with respect to failure likelihood, a priority list of all registered unstable rock slopes will be produced.

This resulting priority list will serve as a source to prioritize mapping and mitigation efforts, with respect to other natural hazards in Norway as well. The knowledge about potential impact areas (primary and secondary) will help avoid building of new critical infrastructure within those areas.

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MAGNITUDE OF REGIONAL EPISODES OF LANDSLIDES IN THE CATALAN PYRENNEES

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Purpose: Landslides in Catalonia periodically cause damage to buildings, infrastructures and eventually loss of human life. The European project PyrMove had as its objective develop cross-border methodologies to reduce the risk associated with landslides. One of the approaches was the study of the Regional Episodes of Landslides (ERML) in the Pyrenees to better explain the landslide hazard to population and as a first step to build a Landslide Early Warning System (LEWS). EMRL episodes describe events in which produce many landslides in a wide region linked to a single trigger usually earthquake or heavy rains.

Methods: To understand the damage caused by regional landslide crises, was carry out the identification and categorization of ERML that occurred in the 20th and 21st centuries in the Catalan Pyrenees. The episodes described were contrasted with some relevant episodes worldwide (17), fact that allowed us to preestablish a qualitative scale magnitude of the ERML that was called mRL (magnitude of Regional Landslides). The mRL was established according to the categorization of 2 variables: (1) the affected regional extent (Ext) and (2) the magnitude of the largest landslide occurred according to the scale used in the ICGC (Mmax). These two variables provide a good reliability for historical episodes and allow to consider all types of slopes movements (surface landslides, rockfalls, debris flow).

Results: Between 1907 and 2022, 9 regional episodes of magnitudes mRL = [1-4] were registered. The triggering factor of all the ERML were rainstorms that occurred mostly in downpour conditions although in some cases the rains can be considered as a persistent type associated to episodes of rain that last more than 2 days. Highlights the case of the episode 2013, in the Val d'Aran, in which apart from the rain, the rapid melting of the snow cover was added. ERMLs are associated with high-magnitude events, despite this, only two episodes have been documented in which the landslides reach magnitude M5: the L'Avellanosa landslide in 1940 (France) and the Pont de Bar landslide from the year 1982 (Spain).

Conclusions: A summary of the main Regional Episodes of landslides is provided with the main data that characterizes them with the extension and magnitude and are related to rainfall distributions.

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REGIONAL INVENTORIES OF DEEP-SEATED GRAVITATIONAL SLOPE DEFORMATIONS: FOCUS ON THE CENTRAL APENNINES

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Purpose: The Deep-Seated Gravitational Slope Deformations (DSGSDs) are large-sized, slow-moving, long-lasting processes that may induce severe rock mass deformation. DSGSDs have been recognized worldwide, including the tectonically active Apennines belt. Despite the several DSGSDs identified so far, we still lack a complete inventory of Apennines cases. While a first inventory was set in the Molise region (Discenza et al., 2023), our work focuses on the Abruzzi region, encompassing the central portion of the Apennines belt. Their distribution can provide hints on the dependence on predisposing (i.e., geostructural setting) or preparatory/triggering (e.g. seismicity or climatic forcing) conditions. The detection of DSGDs in a tectonically active environment (Moro et al., 2012) has also geohazard-related implications, due to their potential to predispose to localized catastrophic failures or earthquake ground motion amplification in damaged rock masses.

Methods: DSGSDs were detected and mapped through remote sensing (analysis and interpretation of stereoscopic aerial photos) combined with field surveys. Records in the geodatabase are reported as polygons (outline of the deforming slope areas) along with information on their kinematic characteristics (type of movement and state of activity), morphometric parameters (area, mean slope, relief energy, etc.) and geological scenarios (Neogene folds or thrusts, Quaternary normal or strike-slip faults), obtained by overlay analyses in a GIS environment.

Results: Our results show a heterogenous distribution of the about 100 detected DSGSDs. Significant lateral spreading processes are concentrated along main thrust fronts, where thick and rigid carbonate sequences lie on on less rigid lithologies (e.g., flysch). Sackung-type deformation is instead frequent along the back-limbs of the main anticline structures or along active fault traces.

Conclusions: In general, even today the most effective methodology for the identification and characterization of DSGSDs turns out to be the synoptic view of the landscape by photointerpretation of characteristic geomorphological indicators (such as double ridges, trenches, and counter-slope scarps); using stereoscopic aerial photos and stereoscopes the error associated with the photo-identification process can be estimated at 15 percent. Field surveys allowed us to validate and refine the remotely-sensed inventories. Although the research must be improved through more accurate analyses in a hazard-oriented perspective, we may draw some preliminary remarks. The distribution of DSGSDs highlights the predisposing role of geological structures inherited from the Apennines build-up, as well as of the present topographic setting, and the preparatory effect of fluvial dynamics following the post-Middle Pleistocene regional uplift of the region. Conversely, the role of earthquake activity and active faulting, which are generally considered potential triggering elements, is definitely more arguable.

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A NEW LARGE LANDSLIDE INVENTORY OF EUROPEAN ALPS

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Purpose: Large slope instabilities include different classes of phenomena such as rockslides, rock slumps, lateral spreads, rock falls and avalanches, rock-mass creep and deep-seated slope gravitational deformations. In an active mountain belt, such as the European Alps, most of these phenomena are active or dormant but can be reactivated or undergo strong changes in style and state of activity. This makes them potentially dangerous for structures and infrastructures due to either a slow-rate deformation or the possibility that fast-moving catastrophic landslide develop within the large instability. The purpose of this work is to present a new large landslide inventory of European Alps and to describe the spatial distribution of landslides with respect to significant controlling factors.

Methods: The inventory extends over the entire European Alps, about 180.000 km2 across Italy, France, Switzerland, Austria, and Slovenia. It was completed by using satellite imagery available on Google Earth© (Google, Inc.) and topographic data at different resolutions (DEMs from 1 m × 1 m up to 20 m × 20 m for different areas) and then validated by comparison with existing local and regional inventories, and the literature. A further step in the analysis includes the comparison with available regional interferometric datasets to identify further movement and to associate a state of activity.

Results: The inventory includes almost 25,000 large landslides spread over the entire Alps. The average density is 0.13 landslides/km2 corresponding to about 14% of the area. The availability of topographic data at different resolution can slightly control both the density and size distribution of mapped landslides. The density ranges from 0.25 landslide/km2 in Slovenia to 0.08 in Italy. In percentage of area, landslides range from 19% in Austria to 7% in Slovenia, suggesting the size of landslides mapped in Slovenia being smaller with respect to other countries, probably due to the effect of the high resolution DEM available for the entire country, but also to the lithology and the local relief. In fact, the median size of landslides ranges from 82,000 m2 in Slovenia to 510,000 m2 in Italy. Among the different controlling variables, lithology and thickness of the ice sheet during LGM show the clearest control. For lithology, DSGSD and rockslides are more common in metapelite, shalestone and paragneiss, while rock fall and rock avalanches occur mainly in limestone, dolostone and orthogneiss. For LGM, we observed a clear increase of landslide density with the ice thickness, up to about 1200 m, suggesting a role of ice debutressing, loading or impact on temperature and hydrologic regime on large landslide occurrence.

Conclusions: The study presents the most complete Alpine-scale large landslide inventory, considering that for various alpine nations no landslide inventory is available. The inventory outclass the previous one prepared by the authors thanks to the level of available morphologic and topographic data. The inventory seems almost complete for some countries where the availability of high resolution DEM allowed to map them more consistently, and will be further improved for other countries, as soon as high-resolution topography will be available.

EARTHQUAKE-INDUCED LANDSLIDES: FROM HISTORICAL DATA TO NEW EMPIRICAL RELATIONSHIPS

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Purpose: We present a new database of historical earthquake-induced landslides (EILs) for the Italian territory, developed in framework of the CFTI5Med historical earthquake catalogue (https://storing.ingv.it/cfti/cfti5/) with a twofold goal: 1) extending back in time the knowledge of seismic induced environmental effects so as to be able to forecast scenarios of future large events (i.e. with M>5.5), and 2) to develop new empirical relationships connecting landslide distribution and seismic parameters.

Method: We first revised the database of seismic-induced environmental effects connected to the CFTI historical seismic catalogue, collecting and analysing new historical sources and revising those already studied in the past. In addition, we analysed recent scientific articles and technical reports and made comparisons with other digital archives such as the CEDIT (https://doi.org/10.4408/IJEGE.2012-02.O-05) and the EEE catalogues (http://eeecatalogue.isprambiente.it/). As a second step, we tried to accurately locate the historical EILs in a GIS environment using the coeval descriptions and comparing them with topographic maps and geographic names. In some cases, it was possible to associate individual EILs with landslides already included and described in the Italian Landslide Inventory (IFFI database https://www.progettoiffi.isprambiente.it/). The third step was aimed at the development of new empirical attenuation relationships using the implemented database. To do so, we related the variation of EILs density with distance from the epicentre as a function of the earthquake magnitude. The seismic events were subdivided into three magnitude classes to account for the different extent of the maximum area affected by EILs and released energy. In addition, using the shake maps of 38 out 159 historical earthquakes of our dataset, we also developed a new empirical relationship relating the variation of EILs density with distance as a function of the peak ground acceleration.

Results: The result of this work is a new database of historical EILs, composed of more than 1,000 landslides associated with more than 150 historical earthquakes or seismic sequences occurred between 117 b.C.E. and 1997. Each EIL is classified on the basis of the accuracy of its location and of the slope movement type. The updated dataset is collected in the new CFTI Landslides database, connected to but independent from the CFTI5Med database, and it is publicly accessible online through a dedicated open-source geographic interface, designed to be interoperable with both INGV and external databases through dedicated web services. As empirical results, we found that the cumulative density of EILs decreases with distance from the earthquake epicentre following a power law relationship and the power law relationship derived from PGA value shows the increasing landslide density with increasing acceleration, defining a threshold value of PGA between 0.2-0.3 g.

Conclusions: The implementation of the new historical EIL database for the Italian territory, on one hand allowed for a better definition of the environmental effects triggered following large earthquakes, on the other hand, dramatically increased the number of data points available for deriving empirical relationships and consequently their statistical significance.

COSEISMIC LANDSLIDES CAUSED BY SUBDUCTION ZONE EARTHQUAKES IN SOLOMON AND VANUATU ISLANDS

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Purpose: Co-seismic landslides caused by strong earthquakes show different spatial patterns in various geographical locations. The 'Pacific ring of Fire' is the most active tectonic formation that is home to many high magnitude earthquakes. The Solomon subduction plate boundary is famous for earthquakes recorded as early as 1900's. Contributing factors of Co-seismic landslides in this region are not fully understood. In this work we present two landslide inventories caused by two recent earthquakes in Solomon (November 2022) and Vanuatu (January 2023) islands of Mw 7 each, from high resolution Planet and Maxar images.

Methods: We investigate various factors such as seismological parameters, geological units and climatic conditions governing the contribution to these co-seismic landslides. To further examine the similarities among subduction zone events that trigger landslides, we compare these inventories with the Porgera earthquake in Papua New Guinea and the Tohoku earthquake in Japan.

Results: Our results indicate that the Magnitude of earthquakes in subduction zones controls the triggering of landslides. Three other non-subduction zone earthquakes from Nepal and China are compared to give a complete outlook of the contributing factors unique to landslides caused by subduction zone earthquakes in these two events.

Conclusions: The focal depth of the earthquakes on shore and offshore do not significantly contribute to the landslide number in case of subduction zone earthquakes while for other non-subduction events the depth of the earthquake controls the size and number of triggered landslides.

SENTINEL-1 SAR BACKSCATTER PRODUCTS FOR EVENT LANDSLIDE MAPPING

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Purpose: Rainfall triggered landslides occur worldwide and cause damages to structures and human life. Obtaining even coarse information on the location of triggered landslides during or immediately after an event can increase the efficiency and efficacy of emergency response, possibly reducing the number of victims. In most cases, however, in the immediate aftermath of a meteorological triggering event, optical post-event images are unusable due to cloud cover. Synthetic Aperture Radar (SAR) sensors overcome this limitation. In this work we explore C-band Sentinel-1 SAR amplitude images to map event landslides.

Methods: Four expert photo-interpreters have defined interpretation criteria of SAR amplitude (i) post-event images of the backscatter coefficient (i.e. β0, the radar brightness coefficient) and of the (ii) derived images of change computed as the natural logarithm of the ratio between the post- and pre-event images. Interpretation of post-event images builds on the criteria of interpretation usually applied to optical images. In the images of change, interpreters identify areas where the change has not been random (i.e. clusters that pop out from the salt and pepper matrix), and decide whether the cluster is a landslide based on its shape. The same team of image interpreters mapped two large event landslides. The first is a rock slide - debris flow - mudflow occurred in Villa Santa Lucia, Chile on 16 December 2017. The second is a rock slide occurred in early August 2015 in the Tonzang region, Myanmar. The landslide maps were prepared on a total of 72 images for the Chile test case and 54 for the Myanmar test case. Images included VV (vertical transmit, vertical receive) and VH (vertical transmit, horizontal receive) polarisation, ascending and descending acquisition geometries, multilook processing, adaptive and moving window filters, post-event images and images of change. For the Chile test case, interpreters mapped the event landslide on an optical post-event image before mapping on SAR images, whereas in Myanmar it was done in the end. Maps obtained from SAR amplitude derived products were quantitatively compared to the maps prepared on post-event optical images, assumed as benchmark, by using a geometrical matching index.

Results: Despite the overall good agreement between the SAR- and optical-derived landslide maps, locally, errors can be due to geometrical distortions, and speckling-like effects. In this experiment, polarisation played an important role, while filtering was less decisive. Results of this study proved that Sentinel-1 C-band SAR amplitude derived products can be exploited for preparing accurate maps of large event landslides, and that they should be further tested to prepare event inventories.

Conclusions: Other SAR bands and resolutions should be tested in different environmental conditions and for different types and sizes of landslides. Application of rigorous and reproducible interpretation criteria to a wide library of test cases will strengthen the capability of expert image interpreters of using such images to produce accurate landslide maps in the immediate aftermath of triggered landslide events worldwide or even train automatic classification systems.

SESSION 3.2

NATURAL FIELD LABORATORIES ON LANDSLIDES

COLLABORATIVE CENTER FOR LANDSLIDES GEOHAZARDS

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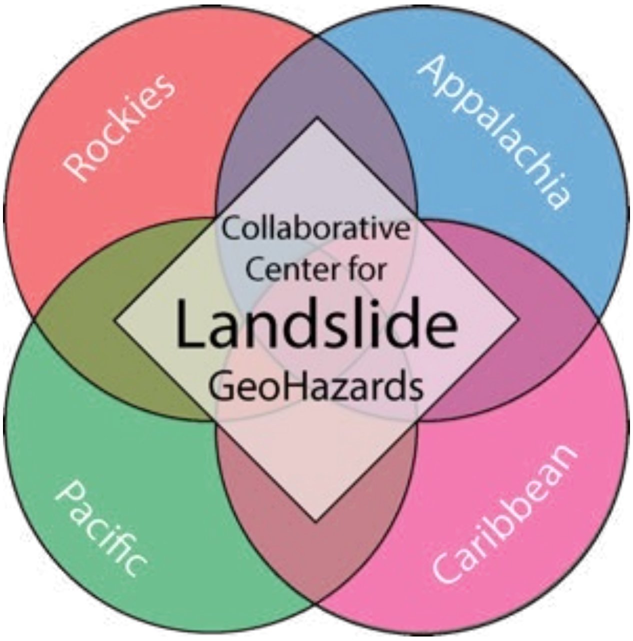
Purpose: Landslides are a common hazard in mountainous terrain worldwide. Worldwide landslides claimed more than 18,000 lives between 1998 and 2017. The National Science Foundation of the United States is funding an initial effort to define a national Collaborative Center for Landslide Geohazards. This activity will culminate in a proposal for a long-term effort. The Georgia Institute of Technology, the University of Puerto Rico at Mayagüez and the University of Colorado Boulder are the initial partners in the endeavor. Ultimately other US Partners will be involved as well as international collaborators. The initial effort uses the Caribbean Island of Puerto Rico as a living laboratory. Puerto Rico is very susceptible to shallow landslides triggered by rainfall, and a wealth of data on the topic has been collected. Ultimately the Center will have integrated and overlapping activities in regions of the US that are most prone to landslides: Appalachia, Caribbean, the Pacific Ranges, and the Rockies.



Methods: The Center has three key focus areas: Research and Innovation, Education and Training, and Community Engagement. The Mission of the Collaborative Center for Landslide Geohazards is to carry out and promote landslide hazard science, training, and community engagement across key landslide-prone areas of the United States. Its Objectives are:
- Explore the fundamental causes of diverse landslide types and cascading hazards;
- Form and Manage a network of integrated institutional efforts across key regions of the nation.
- Build and Curate a platform for fieldwork and modeling tools specific to landslide science;
- Engage and Partner with communities susceptible to landslides via a structured geohazard preparedness program;
- Develop the next generation of diverse leaders in landslides and geosciences.

Results: Four overarching science questions have been defined:
- Predictability – What are the key triggers of landslides? How do they depend on lithology, vegetation, topography, climate, tectonics, history, land use? Develop mathematical models for prediction.
- Observation Systems and Integration of Data – Study existing data sources from a risk assessment value perspective. Investigate technologies to improve on the measurements of key indicator variables.
- What is the relationship between hillslopes, fluvial geomorphology, landslides and related geohazards? What is the risk evolution after large episodic events?
- Impact of expected climate change on landslide susceptibility. Are landslides carbon sinks or carbon sources – under what conditions?

The Center will also work in developing workshops, training, and short course material across its regional focus areas.The engagement of local communities at risk of landslides will revolve around a pilot “LandslideReady” program in collaboration with stakeholders in the regions of interest.

Conclusions: The Collaborative Center for Landslide Geohazards has the potential to transform the way that landslide hazard science and communication are carried out across the United States in a way that benefits society’s needs in the face of climate change and future scenarios.

FIELD MONITORING OF HYDRAULIC SOIL CONDITIONS IN A LANDSLIDE-PRONE TERRACED SLOPE: INSIGHTS FROM MONTEROSSO AL MARE (ITALY)

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Purpose: Shallow landslides due to heavy rainfall represent a common geological hazard that frequently interferes with the anthropic component of the environment, especially in mountainous and hilly regions. In recent years, the frequency of strong rainfall events has increased due to global climate changes amplifying their impact on the environment regarding landslides and other natural disasters. Thus, the importance of understanding cause-to-effect relations between the meteo-climatic stressors acting on soil cover and the induced hydraulic response and failures is evident to mitigate the related geological risk and to calibrate adequate trigger thresholds suitable for early-warning systems.

Methods: With this purpose, a multi-sensor monitoring station devoted to recording both meteorological forcings and hydraulic parameters of the soil has been operating since 2018 on a typical terraced slope located within the Pastanelli-Morione stream catchment in Monterosso al Mare (Cinque Terre, Liguria region, Italy). The Cinque Terre are well-known worldwide and represents a clear example of a man-made shaped area made-up of century-old agricultural terraces retained by dry stone walls. For this reason, a National Park was established in 1999, two years later by its declaration as a World Heritage Site by UNESCO. In the past, several landslide events occurred in this area like the 25th of October 2011 flash flood event, when hundreds of shallow landslides were triggered by extreme rainfall. The installed multi-sensors monitoring system consists of: i) a fully equipped weather station; ii) soil temperature sensors; iii) soil moisture sensors; iv) soil water potential sensors. The devices are installed at different depths to reconstruct a vertical log of the monitored data. All sensors are cable-connected to a datalogger with a 10-minute sampling step and transmitted to a local server by a GPRS wireless connection system that enables remote control of datasets by the users. Before the installation of the monitoring sensors, an engineering geological characterisation of the soil cover was performed through laboratory tests, geotechnical investigations, and geophysical field surveys.

Results: Deductions on hydraulic soil behaviour as a response to meteorological conditions were inferred from the time series acquired over these first years of monitoring, considering a typical geological cross-section of the slope in which the thickness of the soil covers was determined through seismic refraction surveys and dynamic probing tests. In particular, the rainfall regime was characterised in terms of extreme events and prolonged ones and specific cause-to-effect relations with the soil moisture and soil water pressure were derived over two different time scales: i) single rainfall event (i.e., hydraulic response of soil to a specific pluviometric input); ii) seasonal time scale (i.e., typical seasonal oscillation over a year). Soil Water Characteristic Curves (SWCCs) were also reconstructed to estimate how hydrological hysteresis processes affect the investigated soils.

Conclusions: In the future, the monitoring series' systematic analysis will help define the hydromechanical soil behaviour, both in saturated and unsaturated conditions, even in this context of terraced slopes, and evaluate pluviometric thresholds for slope stability purposes at the catchment scale.

ARTIFICIAL NEURAL NETWORK APPROACH TO PROVIDE FAILURE PRECURSORS IN JOINTED ROCK MASS AT THE ACUTO FIELD LAB

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Purpose: Strain effects on jointed rock masses to the action of environmental (and specifically thermal) stressors, to be seen as preparatory factors of possible failures, is up today relevant topic in view of strategies for prediction of rock block instabilities. These strategies that can be implemented are among the most different, but when long monitoring time series are available, innovative machine learning represent useful tools to achieve this goal. For this purpose, data from the multi-parametric monitoring system operating in the Acuto Field Lab (central Italy) were treated following artificial neural network (ANN) approaches able to detect correlation between dependent and independent variables and support the inference of the cause-to-effect relationship between forcing actions and induced deformations before the ultimate failure.

Methods: The Acuto Field Lab, managed by the Earth Sciences Department of "Sapienza" University of Rome, has been operating since 2015 in an abandoned limestone quarry. The multi-parametric monitoring system, set to an acquisition timestep of 1 minute and consisting in a fully equipped weather station, a thermocouple on rock and strain gages, has been installed on 20m3 rock block prone-to-fall. Starting from the already acquired six years monitored time series, an ANN analysis has been performed to recognise out of range deformations (i.e., potentially plastic) cumulated daily as effect of thermal cycles. A training, test and validation datasets were composed of day-by-day rock mass thermal excursion and the related daily strain. About the latter was verified whether its elastic nature, basing on theoretical deformation range based on the suffered thermal excursion and rock linear thermal expansion coefficient of the material, or non-expected (i.e., potentially plastic) strain, when higher or lower than the expected elastic deformation value was registered. A valuable set of environmental potential stressors was associated with the training dataset. It was composed of temperature range calculated the air and rock matrix considering over different moving time windows, the excursion of both maximum and minimum temperatures, air humidity vs. dew point, rainfall, wind intensity.

Results: The ANN was designed to distinguish elastic or plastic rock mass deformation and to discriminate the most significant environmental stressors acting on the jointed rock mass. The classification resulted in a very high-quality performance, with precision and accuracy of about 80% and AUC of 0.87. A Feature Importance Analysis made it also possible to identify the most relevant environmental features. Partial dependence plots allowed to study the relationship between the feature values and the classification obtained.

Conclusions: The instrumentation installed in the Acuto Field Lab offers the opportunity to collect in real-time a large amount of multiparametric data. Our preliminary analysis demonstrates that such instrumental measures set, characterised by high precision and high temporal frequency, represents an optimal application context for machine learning approaches and big data analysis. The results highlight a promising perspective on using neural network methods to systematically investigate the effects of environmental stressors on joint rock mass contexts. These results also represent a valuable starting point toward the implementation of real-time deformation forecasting systems based on IoT technologies.

DEBRISFLOW MODELLING IN KAKHETI REGION (GEORGIA) ON THE EXAMPLE OF RIV. KISISKHEVI AND RIV. KHODASHENI

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The aim of the research is to model geological hazards of riv. Khodasheni and riv. Kisiskhevi gorges, located in Telavi and Akhmeta municipalities (Kakheti region), Eastern Georgia. The study area is distinguished by its complex geological, morphological, tectonic and climate conditions. However, geological hazard modelling of river gorges is very important for their sustainable management, as well as for the implementation of various engineering, agricultural and infrastructural projects.

3 main activities were conducted during the research: 1) Processing of historical studies and reports; 2) Field investigation for identification of all type of geohazards; 3) Processing and modelling the data obtained from the fieldwork. The US Forestry Departments' protocols, indicators (Watershed Condition Framework, 2011) and methodology, moreover, UAV and satellite imagery techniques were used for assessing geological hazards in both river gorges.

All natural conditions, data and information were used to model major landslides and their impact on forming and distributing debris flow events using RAMMS. For both rivers gorges worst case scenarios were modelled (height, velocity, pressure) – landslides cross and dem the river bed, which then is turned into debris flow and poses a threat to the Alaverdi Monastery, nearby settlements, a railway station and other infrastructural facilities.

Based on all of the above-mentioned information, for safety of the population and sustainable development for both river gorges and nearby territories, permanent monitoring systems of vulnerable hazards and other protective and mitigation measures should be implemented.

DAEMON RESISTIVITY SYSTEM: AN ADVANCED APPROACH TO THE MONITORING OF ACTIVE LANDSLIDES

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Monitoring of active landslides is one of the basic premises of understanding their spatial and temporal behaviour. In addition to measuring of displacements using various direct methods (e.g. repetitive measurements of fixed points, extensometric and dilatometric measurements of blocks or tension cracks) as well as indirect methods (radar interferometry, photogrammetry), also parameters of the landslide environment should be measured, especially those related to the water content in the landslide body. Determination of the water saturation of the landslide body is crucial as it is one of the most common trigger factors. And, as the landslide draining is one of the key measures in securing the landslide, its effectivity can be controlled by observations of the water content.

To monitor changes in the water saturation of the landslide body, repeated measurements of the apparent electrical resistivity can be used. In a short term, the changes in the measured apparent resistivity values can be interpreted as changes in water saturation. To be able to calibrate and interpret the measured resistivity values, it is necessary to measure real moisture, using tensiometers (measuring soil moisture tension) or piezoelectric sensors. In fact, the possibility to obtain and display the data in 2D section using the electrical resistivity tomography (ERT) method is a considerable advantage of the resistivity measurements in profile. Changes in the resistivity distribution can thus be observed in section (or even in 3D space in the case of pseudo3D or real3D measurements).

We have been measuring the apparent electrical resistivity on a single profile repeatedly since 2013. During that time, we have gradually progressed from a single repetitive measurement (with 1-month period) on fixed on-surface electrodes, using field measurement equipment, to a fully automated, remotely controlled, subsurface resistivity system capable of measuring continuously if required. This innovative system, we designed for the purpose, allows us to access and control the measuring remotely, as well as adjust parameters of the measurement. At the same time, the system regularly sends the measured data to a remote storage, where the data can be automatically processed and interpreted or displayed graphically almost instantly. This enables us to monitor landslide behaviour virtually in real time.

Using a fully automated resistivity measurement system, that can be operated remotely, we are able to monitor changes in the water saturation of an active landslide. The system is essentially ready to be a part of an early warning system, however, for a fully automatic operation (i.e. including the automated warnings) it is always necessary to define certain threshold values of the measured physical parameter, when the warning is triggered. However, these thresholds can vary considerably depending on the study site and thus always need to be determined locally based on experimental measurements and other available information, e.g. from displacement measurements, precipitation monitoring or ground water level observations in wells.

THE DEVELOPMENT OF A LONG-TERM LANDSLIDE FIELD LABORATORY: EXPERIENCE FROM THE HOLLIN HILL LANDSLIDE OBSERVATORY, UK

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Purpose: The Hollin Hill Landslide Observatory (HHLO) was established 2007 to stimulate collaborative long-term landslide research, and to trial new and emerging geophysical and allied geotechnical and remote-sensing technologies. The observatory is located on an actively failing Lias Group mudstone escarpment, near York, UK (Uhlemann et al., 2017), which is analogous to many lowland, clayey landslides both in the UK and internationally (Lacroix et al., 2020). Here we provide an overview of site development and consider the benefits and challenges of establishing the observatory.

Approach: Initial research focused on geoelectrical methods due to their sensitivity to moisture driven processes (e.g. Uhlemann et al., 2017). Subsequently other novel approaches to geophysical (including seismic and fibre optic technologies), geotechnical, hydrological and geodetic sensing have also been trialled (e.g. Boyd et al., 2021). In doing so we have addressed challenges associated with long-term maintenance of instrumentation at a remote field site and the handling of large and diverse time-series data sets. This has been aided by pursuing a fundamentally collaborative approach involving multiple concurrent projects with numerous partners.

Outcomes: A primary benefit of the HHLO has been as a testbed for novel instrumentation and methodologies in well-constrained field conditions, with advances in monitoring being particularly driven by data fusion and integration. Specifically, research at the HHLO has enabled advances in linked geophysical-geotechnical modelling, landslide process understanding, and the development of a framework for the integration of geophysical imaging into slope-scale landslide early warning systems (Whiteley et al., 2021). Perhaps most importantly, the observatory has served as a focus for multidisciplinary (i.e. geomorphology, hydrology, geophysics, geotechnics) collaboration, educational activities and stakeholder engagement – with many of the technologies and methodologies developed at the HHLO now being applied to many other unstable natural and engineered slopes.

Conclusions: Due to the stochastic nature of landslide systems, the many and interrelated factors contributing to their destabilisation and the multi-scale spatiotemporal processes driving their evolution are best understood through multi-year observations at the whole-slope scale - which cannot be wholly replicated by modelling or laboratory-scale experiments alone. Consequently, it is our contention that field laboratories such as the HHLO, which enable long-term monitoring experiments and the development of practical monitoring solutions, have a crucial role to play in landslide research.

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THERMALLY INDUCED MODIFICATIONS IN SITE STABILITY: LESSONS LEARNED FROM THE NATURAL FIELD LABORATORIES OF THE NW ITALIAN ALPS

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Purpose: The identification of potentially unstable sites and the analysis of the predisposing, preparatory and triggering factors are key steps for the monitoring and mitigation of natural hazards linked to slope instability. Among the methods that allow to investigate these factors, passive seismic monitoring of landslides and potentially unstable rock masses has seen an increase in the number of applications and processing techniques in the last decade. In particular, ambient seismic noise and microseismicity analyses can be used to recognized irreversible modifications in site stability and failure precursors in an early-warning perspective. In addition, seismic parameters generally exhibit reversible variations related to the preparatory factors governing site stability, such as temperature driven modifications. These reversible variations of seismic parameters as a function of the external air temperature fluctuations have been observed and quantified in several natural field laboratories, including the long-term monitored potentially unstable rock masses of Madonna del Sasso (VB) and Ormea (CN), and the rock mass at the top of Bossea Cave (CN), in the northwestern Italian Alps.

Methods: Two key parameters can be extracted from the continuous recording of ambient seismic noise and tracked over time: the resonance frequency of the unstable compartment and the variations in the seismic velocity inside the investigate medium. Apart from the expected irreversible drops preceding rock failure, both seismic parameters undergo reversible variations linked to variations in the air temperature and/or precipitation at the daily and seasonal scale. The analysis and quantification of these reversible changes provides fundamental information on the preparatory factors ruling on site stability. In parallel, microseismic signals, i.e. potentially linked to fracturing phenomena within the investigated volume, can be extracted from the continuous ambient seismic noise series by detection algorithms. The analysis of their temporal rate and the source location can provide additional insights on the acceleration to failure and/ or thermally driven modifications in site stability.

Results: All the long-term monitored natural field laboratories of the northwestern Italian Alps highlighted a reversible and temperature driven modification in the seismic parameters. Resonance frequencies and velocity variations detected from ambient seismic noise analyses returned comparable results which allow to follow the long-term evolution and to recognize the main mechanisms controlling site stability. These modifications were found to be primarily linked to modifications in the fracture opening linked to the rock mass thermal expansion and contraction. The recorded microseismic events showed similar spectral signatures at the different sites. Their hypocenters were located in the vicinity of the most open and pervasive fractures, supporting the hypothesis of a reversible thermal control on the opening and closure of fractures.

Conclusions: The natural field laboratories monitored through passive seismic networks in the northwestern Italian Alps highlighted a high sensitivity to temperature variations. Their quantification is not only useful to properly detect irreversible modifications in an early warning perspective, but also provides important insights on the driving mechanisms controlling site stability.

QUANTIFICATION OF THE SEISMIC RESPONSE OF UNSTABLE SLOPES AND ITS TIME VARIABILITY

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Purpose: In recent years, efficient geophysical and seismological measurement tools have been developed that allow for the seismic characterization and monitoring of slope instabilities. With these techniques, instabilities can be detected, mapped, and monitored with only a few hours of ambient vibration recordings, or by continuously assessing the site response using ambient vibrations and earthquake recordings. We combine seismic observations either with groundwater-table variations measured directly or by comparison with precipitation measurements and temperature. We explore the potential link between the vibrational behavior towards engineering-geological characteristics, the kinematic behavior and the degradation of the slope.

Methods: We analyze ambient vibrations and earthquake ground-motion by performing repeated short-term measurements at several sites in Switzerland, and continuous seismic monitoring at permanently installed sites (Figure 1). Some instabilities show normal-mode behavior typically observed for structures with distinct partial volumes, where the wave field at resonant frequencies is oriented perpendicular to the fractures. Other slopes with highly fractured material can be characterized by a one-dimensional subsurface structure in which surface waves can be used to infer the depth of the instability. The amplitude of ground motion amplification is measured with site-to-reference spectral ratios (SRSR) of ambient vibrations relative to a reference rock site. Absolute amplification of earthquake ground motion with respect to a fixed theoretical reference rock is estimated for all earthquakes of a certain size using empirical spectral modelling. Ground motion properties are continuously monitored at permanent sites, and compared to the kinematic properties of the instability and environmental parameters.

Results: Observations from ambient vibration measurements and earthquake excitation provide similar seismic response of the instabilities. They are subject to seasonal changes due to rain, snow and temperature fluctuations (permafrost and non-permafrost sites, e.g. Gemsstock and Preonzo), as well as the internal degradation of the rock mass and the surface deformations at slopes with large displacements (e.g. Brinzauls). The results from our studies show that vibration measurements allow for a rapid characterization of potentially unstable slopes. It is possible to distinguish unstable from stable regions and thus estimate failure-prone volumes as well as to detect large fractures that are not visible at the surface. Normal-mode analyses provide the resonant frequency, damping parameters, and resonant mode shapes (polarization) of the vibrating structure. The mode shapes, especially for higher vibrational modes, can be used to map the fracture system of the instability. All these parameters are continuously monitored at permanent sites and might allow the detection of internal changes of the instability.

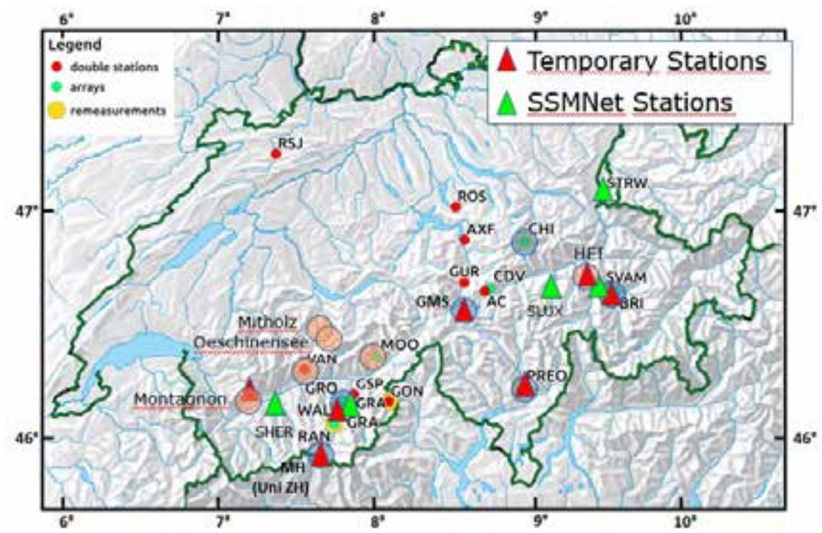

Fig. 1: Overview of instabilities investigated with different geophysical and seismological methods.

Conclusions: Local amplification levels and polarization of ambient vibrations and earthquake ground motion are related to the degradation of an instability, environmental parameters, and the characteristics of the slope structure in relation to the fracture system. Ground motion parameters are very sensitive to small changes in the internal structure of an instability. Seismic methods can therefore complement other techniques for monitoring slope instabilities, offer a wide range of applications, and can improve our understanding related to earthquake-induced mass movements.

LANDSLIDE MONITORING THROUGH THE USE OF MULTISPECTRAL MONITORING TOOLS: THE CASE STUDY OF THE POGGIO BALDI MONITORING LABORATORY

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Purpose: This works aims to a better characterization of rockfall to provide a contribution to their spatial and temporal prediction and to the development of early warning systems. To achieve this goal is crucial to study the correlation between causes and effects of rockfall phenomena through the integrated use of acoustic, optical, radar, laser and meteorological monitoring tools available at the Poggio Baldi Natural Laboratory of the Department of Earth Science. Specifically, the study aims to understand the relationship between rockfalls and predisposing and triggering factors such as thermal, seismic, and meteorological stress.

Methods: Different remote sensing tools are currently used to monitor and predict the activity of the main rock scarp. Images acquired from the optical tools are processed by specific change detection algorithms developed within the proprietary software IRIS developed by NHAZCA SRL. Point clouds acquired during monitor campaign are used to perform 3D geostructural analyses to quantify the involved volumes of rockfalls. GB-InSAR data are used to produce debris talus displacement maps while doppler radar data are used to visualize trajectory and velocity of the rockfalls. The records obtained from the microphone and the seismic sensor are analysed whit specific software and provide to a constant coverage of the site The weather station provided useful information to understand weather conditions of the site that could result in triggering factors such as rain and wind speed.

Results: The data acquired from different tools allowed for high spatial and temporal resolution data, providing detailed information about the activity of the main rock scarp at the Poggio Baldi laboratory. The multi-temporal comparison of point clouds shed light on the most active zones along the scarp that can be divided into 4 areas where rock-block sizes were derived based on the discontinuities orientation and spacing. Change detection analysis highlighted the most active areas and involved volumes, while gigapixel images helped identify small rockfall precursors. Doppler radar tracking enabled the evaluation of trajectories, impacts, and fragmentation. Triggering thresholds set up on the phonometer allowed the recording of all rockfall events while reducing false positives. Integration of acoustic data with microseismicity analysis refined true rockfall events and identified potential relationships with environmental factors. High-resolution weather data provided insights on meteo-climatic conditions, such as wind gusts, which are important for rockfall occurrences. The integrated use of multi-spectral remote sensing tools provided a complete overview of the rockfall activity, allowing for cross-validation of results and calibration of tools.

Conclusions: The Poggio Baldi laboratory exemplifies the effectiveness of multiple remote monitoring tools in understanding and managing landslide hazards. Innovative technologies and collaboration with different companies have allowed for high-resolution data, including deformation pre-rockfall, frequency analysis of volume, and understanding of the relationship between triggering and predisposing factors for rockfall Overall, the application of multiple remote monitoring tools provides high-resolution data that contributes to an improved understanding and management of landslide hazards, potentially enabling the development of early warning systems and risk mitigation strategies.

WEATHERING INFLUENCE ON DURABILITY OF FINE-GRAINED LITHOLOGICAL FLYSCH COMPONENTS IN ISTRIA PENINSULA, CROATIA

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Purpose: Fine-grained lithological flysch rock mass components such as siltstones are highly susceptible to weathering, which causes rapid changes in their geotechnical properties, that results in slope instability. In this study, the effects of weathering on the durability of siltstone samples of different weathering grades from the Istria Peninsula, Croatia, were investigated. Determining the durability of siltstones using only standardized slake durability tests (SDT) is not sufficient, because fragmented siltstone samples reach a high slake durability index (Id2) but are highly degraded [1-3], Figure. Therefore, the fragment size distribution of the siltstone sample retained in the drum must be quantified after each drying-wetting cycle of the test. Beside the standardized parameter Id2 [4], calculation of additional parameters such as the disintegration ratio (DR2) [1] and the modified disintegration ratio (DRP2) [2] is needed to indicate not only the durability but also the manner of disintegration of siltstones.

Fig. 1: Fragments of FR siltstone sample retained in the drum after five cycles in SDT [3].

Methods: Tests were performed on irregular block samples of fresh (FR) and moderately weathered (MW) siltstone. The standardized SDT was performed in five drying-wetting cycles, and in addition, the nature of slaked material retained in the drum was quantitatively analyzed and the grain size distribution was determined after each test cycle. Beside Id2, additional parameters, DR2 and DRP2, were calculated

Results: The results of SDT after the second cycle for siltstones of different weathering grades (Table) are explained. The FR siltstone samples were more durable and less susceptible to degradation than the MW siltstone samples. According to the standardized classification, the siltstone samples are classified in a higher durability class than when classified based on fragmentation during SDT.

Table: SDT results in the second cycle for FR and WW siltstones [3].

Sample	Id2 [%]	DRd	DRP2
FR	97.03	0.81	0.19
MW	95.39	0.79	0.21

Conclusions: The use of Id2 does not adequately explain the slaking behavior of siltstones because fragmented samples are highly degraded by SDT. Therefore, additional parameters DR2 and DRP2 must be calculated to indicate not only the durability but also the manner of disintegration of siltstones. SDT require fewer drying and wetting cycles to reach the maximum possible degradation. The standard Id2 increases the slaking resistance of the tested siltstone samples by at least one class.

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SESSION 4.4

SHALLOW LANDSLIDES: MONITORING, MODELING, PREDICTING

DEBRIS FLOW SUSCEPTIBILITY MAPPING USING FLOW-R MODEL IN MAE PHIN WATERSHED, UTTARADIT PROVINCE, NORTHERN THAILAND

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Extremely intense rainfall of May 2006 triggered a big landslide disaster in Mae Phun watershed. This catastrophic debris flows caused loss of life and properties of local people in the area. Landslide flow path prediction is important for determining the flow route and the depositional area, which are essential elements for producing landslide hazard maps and contributing to landslide risk assessment. Therefore, this study focused on determining debris flow susceptibility mapping using Flow-R model which is developed for flow path assessment of gravitational hazards based on the major input of a digital elevation model (DEM).

The quantitative Flow-R method was tested in order to define the potential source and debris flow susceptibility for the Mae Phun watershed, Uttaradit province. The major aspect of flow path modelling is to define the potential source areas and asses the spreading areas. Potential source areas were identified based on digital elevation model and the defined data set of slopes, water input, flow accumulation and curvature. Spreading area assessment was based on the flow directions algorithms and the energy-based algorithms which determine the run-out distance. The susceptibility level of debris flow was calculated and classed by standard deviation methos.

The result showed 916 source points and run-out areas with the susceptibility level. Landslide scars mapped by Google Earth image taken in November 2006 and landslide susceptibility map of Uttaradit province was used for model validation. The source areas and the run-out results obtained by the model were 15% matched with the available landslide inventory data set. This possibly be affected from the medium resolution of 10 m. DEM as well as the vary of geological units of the area which is the key factor that control the landslide susceptibility in this watershed. The path and run-out areas were mostly matched with the 2006 event.

The Flow-R method allowed us to quantitatively determine the potential source areas and calculate potential spreading and runout. Not only did the debris flow susceptibility map correlated well with known events and has also demonstrated other potential channels that could be susceptible to debris flows. The validation with known events may or may not exactly match with the size of the past debris flow deposits. However, the model could possibly be used for predicting the debris flow source areas and spreading run out at regional scale.

MODELLING EXPOSURE TO DEBRIS FLOWS IN MARLBOROUGH, NEW ZEALAND

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Purpose: Debris flows are one of the most destructive landslide processes globally, causing severe damage to critical lifelines and numerous fatalities. The infrequent nature of debris flows means our observational records are sparse and exposed populations are often largely unaware of the hazard posed, leaving many areas unprepared. In New Zealand, there is a relatively short recorded history, with limited observations of historic debris flows, meaning many catchments experiencing contemporary debris flows have no known previous events. Marlborough Region is particularly prone to debris flow hazards and in the last 20 years has experienced at least four widespread debris flow-triggering events. This research assesses the exposure of communities and infrastructure in the Marlborough Region to modelled debris flow runout.

Methods: We use the open-source Flow-R model to simulate the runout of debris flows across the Marlborough Region. We manually identify potential source areas based on topographic attributes and model propagation in Flow-R using the modified Holmgren spreading equation whilst varying the minimum reach angle to explore the effect. We estimate exposure based on the intersection of population (building footprints) and critical infrastructure with the various modelled runouts.

Results: The results show a considerable degree of exposure of population, buildings, roads and rail to debris flows across the Marlborough Region. Whilst a large proportion of the debris flow hazard is located high in the catchments, away from population centres and infrastructure, there is still a substantial amount of exposure across the region. In particular, while the majority of the exposed population and buildings are located in the main urban areas of Picton and Waikawa, infrastructure exposure is consistent across the region. Some of the main transport routes, including State Highways 1 and 6 (SH1 and SH6), and the Main North Railway line (MNL) are particularly exposed at multiple locations, highlighting a key risk to national supply chains since SH1 and the MNL provide the main links between the North and South Islands. Local roads connecting remote rural communities are also significantly exposed, highlighting the potential for populations to be isolated during major rainstorms.

Conclusions: The results emphasise that there appears to be a significant level of exposure throughout Marlborough to debris flow hazard. Given the short recorded history of New Zealand, many of these exposed locations have no recorded history of debris flows, suggesting many residents are unaware of the hazard posed. With both local population and tourism in Marlborough growing, there is an urgent need to better understand the vulnerability of communities and critical infrastructure to debris flow hazards in order to identify, quantify and reduce the corresponding risks. In particular, with climate change forecast to increase the frequency and intensity of rainstorms in the region, debris flows are expected to present a substantial risk to life and infrastructure across the region. Accounting for this risk in future developments and infrastructure projects are critical for the Marlborough Region as well as New Zealand as a whole.

ON THE USE OF RAMMS::DEBRISFLOW FOR MODELLING THE RUNOUT OF SHALLOW, UNCHANNELED LANDSLIDES IN NORWAY

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Purpose: The Norwegian Water Resources and Energy Directorate (NVE) has since 2009 had the national responsibility for reducing the risk of damages associated with landslides, as well as avalanches and flooding. Among activities that also include planning mitigation measures and issuing process-specific alerts, hazard mapping occupies a central place. While mapping is mostly done by engineering companies hired through tenders and framework agreements, it requires updated technical guidelines to secure consistent approach and results. Even though the guidelines do not mandate specific commercial products such as runout models, technical reports connected to the guidelines do recommend “best practice” for use of widely available modelling tools. The RAMMS software suite has established itself as a tool of choice for most practitioners working with natural hazards in Norway. The RAMMS::Debrisflow module was developed to simulate the runout of muddy and debris-laden flows in complex terrain. However, shallow landslides that release in till-covered slopes and develop through non-channeled terrain are also a recurrent problem in the Norwegian valleys. Minor adjustments of the Voellmy friction coefficients are needed for RAMMS::Debrisflow to acceptably describe the runout of channeled mud or debris flows, but the simulation of unchanneled landslides using similar friction parameters often yields unrealistically short runouts. To address this, as a contribution to our hazard mapping guidelines, a little research project was carried out to see what approach and set of input parameters could be recommended for modelling shallow, unchanneled landslides in RAMMS::Debrisflow.

Methods: Twelve landslides that occurred between 2003 and 2019 were back-analyzed with RAMMS::Debrisflow. This was first done by using “standard” friction coefficients proven to work satisfactorily with channeled flows. Simulations were repeated with much more conservative friction coefficients that experiences in Norway have shown to be suitable for modelling slushflows. None of these preliminary simulations made use of the software’s erosion algorithm. All of them consistently underestimated the landslides’ runouts when compared to observed runouts. In the following simulations, the erosion algorithm was used, and different combinations of the controlling parameters “erosion rate” and “potential erosion depth” were tested. Nearly all simulations used LiDAR-based DEMs from prior to the landslide events, to eliminate the effect that the post-landslide topography would have on the modelled runout.

Results: For all 12 study cases, an acceptable match between modelled and observed runout was achieved by combining standard friction coefficients validated for debris flows with a specific value of “erosion rate” and a “potential erosion depth” to be adjusted based on the slope height.

Conclusions: The modelled runouts for the single study cases could probably be better fitted to observations by further, site-specific tweaking of the coefficients. Yet the purpose of the study was to recommend a simple approach and a reasonable set of parameters for use in hazard mapping work where no calibration event is available, and in this sense the results were judged to be more than acceptable. The recommended approach requires users to define release areas and erosion zones based on morphological elements detectable on hillshade maps. The recommendations are now used by Norwegian practitioners.

AUTOMATED DELIMITATION OF SHALLOW LANDSLIDE HAZARD INDICATION ZONES USING HIGH-RESOLUTION SLOPE STABILITY AND RUNOUT MODELING AT REGIONAL SCALE

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Purpose: Regional hazard mappings are important tools for integrated risk management. More than 15 years ago, large-scale landslide modeling in Switzerland was carried out to indicate potential hazard areas within the framework of SilvaProtect-CH. Since then, landslide models suitable for such applications developed continuously and are currently able to implement the effect of forest vegetation on slope stability assessments at a more detailed level. The aim of our study was to model shallow landslide hazard with and without the forest effect over the entire Principality of Liechtenstein (FL, approx. 158km2).

Methods: We combined the SlideforMap model, which uses a probabilistic finite slope approach, to simulate slope failure probability with the probabilistic hillslope debris flow model SlideForce to simulate landslide runout. The input topography was based on a 0.5 m-resolution digital terrain model which also served for defining input soil characteristics in combination with geological maps. The forest structure was defined by individual tree positions and diameters derived from individual tree detection and statistical modeling. The slope stability simulations were performed at 2m resolution with and without forest effect for the three standardized precipitation scenarios (30-year, 100-year, and 300-year return period) defined as 42 mm/hr (30-yr), 51mm/hr (100-yr) and 60mm/hr (300-yr). Resulting cells with a failure probability of >50% were aggregated to 5m resolution to generate start cells for the runout simulations. For each of these cells, 10 repetitions of runout simulation were performed using the modeled landslide volumes. Based on the aggregated reach probability values, hazard indication zones were automatically delineated. The results were compared with 382 mapped historical landslides caused by an intense rainfall event in August 2005 (corresponding to a 30-yearly event).

Results: The mean simulated failure probability within the historical failure zones for scenarios with forest influence was 33% (30-yr), 37% (100-yr), and 42% (300-yr). The simulated reach probabilities and delimited hazard indication zones showed a good agreement with the historical events as well as post-event aerial imagery except for occasional underestimations of the runout. The larger discrepancies between simulated and mapped runoff zones seem to be due to high fluidification of the sliding masses evolving in hyperconcentrated flow.

Conclusions: We conclude that the combination of slope stability simulations with explicit consideration of the forest effect at 2m resolution in combination with landslide runout simulations at 5m resolution with plausible results is possible for very large areas.

MULTIDISCIPLINARY APPROACH FOR ANALYSIS OF COLLAPSE PROCESSES AND TRIGGERING THRESHOLDS UPDATE IN A DOWNSCALED SHALLOW LANDSLIDES SIMULATOR

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Purpose: The aim of this work is to study in controlled scenarios the evolution of the seasonal processes that lead to the collapse mechanism in shallow landslides. These are particular type of failure which involve reduced part of soil and are triggered by intense rainfall events. Since the middle of the 20th century, heavy precipitation events have been more frequent and intense and in light of the current climate crisis, it is of paramount importance to update the triggering thresholds for these movements.

Methods: To better comprehend the evolution of the processes of water circulation inside the soil and the linked collapse mechanisms, a multidisciplinary approach involving photogrammetrical and geophysical methods had been exploited. A downscaled landslide simulator at the Gap2Lab at the Politecnico di Milano, have been used with different type of material (sand and gravel) with various condition of compaction, water content and have been tested under several simulated rainfall events. Ad hoc developed devices, such as tensiometers equipped with porous cups and soil moisture sensors, have allowed the collection of data about the pore water pressure, volumetric water content and level of saturation. Moreover, the use of optic fibers, have provided information related to the deformation of the soil and the formation of tension fractures.

Results: Through the information obtained from the electrical tomography (georesistivimeter IRIS Syscal Pro), it was possible to visualise the formation of cracks within the landslide body in advance, also allowing considerations regarding the different water contributions of the simulated rainfall and the initial water content in the soil. These data have been confirmed by the deformation obtained from the optic fibers and from the cameras installed which can detect, thank to Direct Image Correlation (DIC) method the movement of the soil portions. Different rainfall intensities as well as different starting conditions of saturation, compaction and inclination led to various time of collapse which can be compared with mathematical models. At the same time, different methods of supplying water to the landslide body caused different types of collapse with different depths, amounts of material involved and velocities.

Conclusions: Data obtained from the three methodologies in these downscaled simulations can be exploited for the update of triggering thresholds according to the various boundary conditions imposed by the different possible scenarios related to the climate change.
In fact, Initial conditions with dry soil and rainfall with varying intensity for different time intervals were tested. The methodology employed act as a cross-check on the evolution of processes within the terrain and provide a complete picture of fracture formation in the landslide body.

INFLUENCE OF SOIL PIPING ON HYDRO-MECHANICAL RESPONSE OF SHALLOW LANDSLIDES

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Purpose: Subsurface erosion, or soil piping, occurs in slopes and embankments when flowing water progressively erodes the soil forming an open void or pipe. Piping is a major source of soil erosion worldwide and leads to the formation of preferential flow paths within the soil that can significantly impact hillslope hydrology. Previous work has found connections between soil pipes and landslides. Researchers have shown piping can provide a conduit to transmit pore pressures, which may increase or decrease matric suction within a slope and therefore stability. There is still limited understanding of the factors that control pipe collapse and how water within the pipe influences moisture and suction levels within a slope. This limits engineers' and geoscientists' ability to understand and model the effects of soil piping on the stability of shallow landslides. We seek to help fill this gap using experiments and validated numerical models to examine the influence of soil pipes on matric suction conditions and internal deformation in a shallow landslide.

Methods: We have performed a series of experiments on model slopes with pre-existing macropores to investigate how unsaturated soil properties influence the growth and collapse of soil pipes in slopes. The slopes are constructed with a small void meant to simulate a macropore to induce preferential flow and erosion. The slopes were subjected to varying rates of subsurface flow and artificial rainfall and instrumented with sensors to measure changes in suction and moisture content during the test. We also monitored pipe flow, sediment concentration, and changes in pipe features during the experiment, along with deformation of the slope. We then used the experimental results to validate a numerical model examining initiation and subsequent deformation of shallow landslides in slopes with and without pipes.

Results: The experimental results show that the erosion rate in the pipe and the soil's ability to hold a stable arch is sensitive to the initial soil density, water content, flow conditions and pipe location within the slope. Changes in water content and suction within the slope were very sensitive to water flow conditions in the pipe. Periodic collapses were observed, which led to sudden increases in pressure within the pipe and increased flow through the soil matrix around the void. Transient numerical simulations were validated using the experimental data and then used to examine the likelihood of shallow landslide triggering in slopes with and without pre-existing pipes. The simulations are then used to examine the deformation patterns at a shallow landslide in west Alabama with known piping features.

Conclusions: Soil pipes have been observed in many shallow landslides, but there is still a limited understanding about how the formation of pipes influences landslide deformation. This study uses a combination of experiments and numerical models to explore how hydro-mechanical conditions within the slope influence the progression of piping and changes in matric suction with slopes. Improved understanding of soil piping is expected to provide better understanding of triggering and deformations in shallow landslides.

THE IMPACT OF SOIL DEPTH ESTIMATION IN PHYSICALLY BASED SHALLOW LANDSLIDE MODELLING

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Purpose: Shallow landslides mobilize the first few meters of soil cover following significant rainfall events, damming rivers, damaging crops and causing fatalities. The modelling of landslide susceptibility aims to predict where they occur to reduce their impact. However, it can be complicated to do so: data is oftentimes not available, hard to gather or difficult to translate into modelling in a reliable way. The present works aims to evaluate the performance of soil depth maps, reconstructed using different techniques, in identifying shallow landslides.

Methods: A probabilistic version of the physically based landscape evolution model Lapsus-LS was chosen. It requires as inputs a Digital Terrain Model, range values for geotechnical parameters, a soil depth map and a land use map. An area is considered at risk if predicted as such over 50% of iterations. Performance is evaluated by calculating the Area under the ROC curve: a value indicating the accuracy of the model. The chosen test site is that of Rio Vergomberra (Canneto Pavese, PV), a 0, 54 km2 catchment located in the hilly region of the Oltrepò Pavese (Italy). The area, characterized by silty soils, is prone to the formation of rainfall-induced shallow landslides. The four tested soil depth maps were calculated as such: (a) a constant 1m depth map, (b) a soil depth map calculated using a methodology created by Zizioli et al. 2013 (taking into account topographical factors) for an area located in the Oltrepò Pavese (c) a map obtained with the Ordinary Kriging of the soil depth measured from 66 boreholes (as part of the LIFE-DRIVE and VIRECLI projects) (d) a map calculated through Co-Kriging, using the slope angle as co-variate, of the soil depth measured in the boreholes. To validate the results, the location of the unstable cells was compared to the location of seven past landslides which have occurred in the area.

Results:

Method	AUC
1m map	0.91
Zizioli map	0.84
Ord. Krig.	0.85
Co-Krig.	0.67

Conclusions: The AUC seems to indicate that a constant 1m soil depth map is better for landslide prediction than more complex maps. It must be noted that the current soil depth models cannot account for over a decade of soil loss, which has occurred in the area, whereas the 1m soil depth value is likely closer to the actual 2009 soil depth, resulting in a better performing model.

References

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IMPLEMENTATION OF A SLOPE STABILITY METHOD FOR RAINFALL-INDUCED SHALLOW LANDSLIDES IN THE CRITERIA-3D MODEL AND ANALYSIS OF A CASE STUDY IN OLTREPÒ PAVESE

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Purpose: The present research deals with the implementation of a slope stability method for rainfall-induced shallow landslide in the agro-hydrological physically based model CRITERIA-3D, and its validation on an experimental slope. This updated version of CRITERIA-3D is intended as a benchmark model for small catchments. This work aims to be a forward step in the creation of a proper Landslide Early Warning System (LEWS) for the prediction of shallow landslides in response to extreme climatic events for civil and environmental protection actions.

Methods: CRITERIA-3D is an open source model (https://github.com/ARPA-SIMC/CRITERIA3D). It is written in C++ and is based on a pixel-by-pixel structure acquired from a DEM. It is composed of two main modules: the first one deals with hydrological phenomena, and the second one is related to the geotechnical aspects. The hydrological component is based on 3D Richards' equation for subsurface unsaturated flow and on Darcy's law for the saturated subsurface flow, solved through the Integrated Finite Difference formulation. The surface flow is computed through the two-dimensional parabolic approximation of the St. Venant equation, using Manning's equation for motion. The geotechnical component is represented by a Limit Equilibrium Method (LEM) equation based on the suction stress concept, in order to consider the unsaturated soil conditions. Soil spatial variability and stratigraphy can be taken into account by specifying geotechnical parameters of different soil layers, based on a soil map as input. CRITERIA-3D is innovative because it is coupled with conceptual models that account for snow accumulation and melting, soil evaporation and plant transpiration component; this latter is based on the Penman-Monteith method. Over space and time CRITERIA-3D accounts for plants activity by the provision of a land use map, a rooting depth besides a roots distribution scheme, and the Leaf Area Index (LAI) development throughout the year. The model is capable to account for different phenological phases of the species that are present in the study area. CRITERIA-3D has been validated referring to an experimental slope in Northern Italy (Montué, Oltrepò pavese) where shallow landslides occurred in 2014 on abandoned vineyards.

Results: The application of the model in the test site showed good agreement with respect to field data concerning the water content estimation. In this research we show the model simulation of the dynamic and distribution of the unstable pixels during the observed landslide triggering period at different depths, from surface to the maximum soil depth.

Conclusions: Future development of the research will be the validation of CRITERIA-3D on different sites and for different plants associations. Assuming CRITERIA-3D as a benchmark model, further more easily extendable and simplified models will be tested comparing the respective results with those obtained by CRITERIA-3D.

IMPROVED LANDSLIDE SUSCEPTIBILITY MAPS - EXAMPLE FROM THE ENTREMONT DISTRICT (VALAIS, SWITZERLAND)

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Regional susceptibility maps depict areas potentially affected by shallow landslides or other gravitational natural hazards; they are therefore an essential tool for land-use planning by highlighting exposed infrastructure. Traditionally, susceptibility maps are binary (exposed or not), whereas novel maps combine high-resolution datasets and advanced computer models to define different susceptibility levels for both failure and runout modelling.

Here, we use high-resolution digital elevation models, vectorized geological and land-use maps along with the numerical model Flow-R (https://www.terranum.ch/en/products/flow-r/) for a novel susceptibility map for shallow landslides in the 680 km² Entremont district (Valais, Switzerland).

Potential source areas for shallow landslides are identified using an infinite slope stability model approach implemented within a SInMap-based inhouse GIS model. For each loose sediment formation and land-use type we define a range of geotechnical soil characteristics (cohesion, friction angle, transmissivity) that are used in the stochastic slope stability model, which computes the spatial and probabilistic distribution of the safety factor. We derive the geotechnical characteristics from literature, laboratory tests and past experiences, but also by iterative adjustment in comparison with landslide inventories. Defining different thresholds in the safety factor probability distribution allows distinguishing several susceptibility levels for the potential landslide source areas.

From these source areas, we model the runout areas using the Flow-R software, which is a spatially distributed empirical model for the propagation modelling of mass movements at regional scale. Flow-R combines a spreading algorithm controlling the path of mass movements with a simplified friction-limited model determining the runout distance. The reliable and well-known reach angle approach is chosen as friction model, as it can easily be calibrated using inventories of past landslides. For this calibration we assess the percentage of landslide events fully encompassed by runout models with different parameter sets (varying reach angle, maximum velocity, and degree of channelization in the spreading etc.). Moreover, for shallow landslides, we distinguish between simple rotational slides with short propagation distance and flow-like mudslides with longer runout.

Using scenarios of runout model parameters along with the sources' susceptibility levels allows distinguishing between extreme events (with low failure susceptibility, low reach angles and high velocity thresholds) and rare or current events (with high failure susceptibility, higher reach angles and lower velocities). The improved resolution and level of detail of these novel susceptibility maps greatly improves the maps' practical use for land-use planning and hazard and risk management by focusing costly field investigation and mitigation measures to critical areas.

Finally, in the framework of the Digital Twin of Alps initiative funded by the European Space Agency, we develop a prototype nowcast and forecast warning system for shallow landslides in the Entremont district. We combine the landslide susceptibility map with triggering factors comprising snow melting, rainfall measurements and precipitation forecasts for the next 72 hours. If these water inputs exceed thresholds derived from intensity-duration relationships, a warning for shallow landslide is triggered and the extent of the potentially affected area is computed. Ultimately, we aim to expand this prototype early-warning system for shallow landslides to the entire Alps.

SESSION 2.12

LANDSLIDE EARLY WARNING SYSTEMS: INNOVATIONS AND APPLICATIONS (part II)

PROBABILISTIC LANDSLIDE PREDICTIONS AND HAZARD COMMUNICATION IN DATA-SPARSE REGIONS OF SOUTHEAST ALASKA, USA

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Purpose: Following a fatal debris flow in 2015, community leaders and technical experts in Sitka, Alaska, USA, determined the need for a landslide early warning system. Community partners identified several criteria necessary for a landslide early warning system in Sitka, including high geographic specificity, contextual information for a non-technical user group, warnings that accommodated varying risk tolerance within the community, and equitable public access. To compound the challenge of meeting these criteria, both rainfall and landslide data are scarce throughout Southeast Alaska. Here, we present two innovations we implemented to address these challenges in the recently launched landslide warning dashboard: sitkalandslide.org.

Methods: First, we evaluated strategies for training shallow landslide forecasting models with a very limited record of landslide-triggering events, which is a typical limitation in remote, sparsely populated regions. We used information criteria (Akaike, Bayesian, and Leave-One-Out Information Criterion) to compare models trained on cumulative precipitation at timescales ranging from one hour to two weeks. We employed both frequentist and Bayesian logistic regression and Poisson regression to estimate the daily probability and intensity of potential landslide occurrence. We also conducted a series of workshops and user-testing to determine the most effective type and platform for communicating warnings. Based on this input, we iteratively designed a public-facing dashboard with a team of geoscientists, social scientists, community leaders, and the web development firm Azavea (now Element 84) for use by community members and emergency managers.

Results: We found that, in Sitka, three-hour precipitation totals were the best predictor of elevated landslide hazard and including antecedent precipitation (days to weeks) did not improve model performance. We then evaluated the best-fit models using leave-one-out cross validation as well as by testing a subset of the data. We found that probabilistic models trained with few landslide-triggering and many non-landslide-triggering events could effectively distinguish days with landslides from days without. We used the resulting estimates of daily landslide probability to establish two decision boundaries for three levels of warning (Low, Medium, High). These levels are displayed on the dashboard, which provides situational awareness and contextual information for the three warning levels. The dashboard has been accessible to the public since May 2022 and has successfully predicted hundreds of no-landslide days, with one false alarm in the “medium” risk category on October 15, 2022, and no missed alarms.

Conclusions: Through collaboration with the community of Sitka, we launched a situational awareness dashboard to describe current and predicted landslide hazard in the community. This tool implements novel application of statistical models to a sparse landslide inventory and addresses community-identified needs for regional specificity, multiple levels of warning, and contextual information designed for a non-technical user group.

IDENTIFYING CRITICAL RAINFALL INDICES AND DEVELOPING PROBABILISTIC RAINFALL THRESHOLDS FOR RAIN INDUCED LANDSLIDES IN SRI LANKA

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Purpose: Rain induced landslides are a major natural disaster that cause fatalities and extensive damages to infrastructure and nature. Accurate and efficient landslide early warning are crucial to mitigate the devastating effects of landslide disasters. However, traditional landslide early warning models that rely on empirical and deterministic approaches have limitations due to the uncertainty of slope conditions and causative factors. While rainfall being the most critical causative factor for rain induced landslide, different rainfall indices are being used for defining the threshold values, and determining the best index or combination of indices are critically important. Advances in Artificial Intelligence (AI) and Machine Learning (ML) provides opportunity to perform extensive statistical analysis on multiple parameters to evaluate their influence on landslide triggering. Also, probabilistic approaches can accommodate the uncertainty of other causative factors. This study is focused on the recent landslides occurred in Sri Lanka, which is a tropical country which receive more than 3000 mm annual rainfall. The objectives of this study are to:
• Identify the key rainfall indices that contribute to the occurrence of landslides in Sri Lanka.
• Develop probabilistic rainfall threshold values to estimate the failure probability and validate the accuracy for issuing early warnings.

Methods: The rainfall records of the landslide prone areas and the historical landslide data of Sri Lanka were obtained from the Realtime Rainfall Measurement System (RRMS) and Landslide Inventory Management System (LIMS) of National Building Research Organisation (NBRO), Sri Lanka, respectively. As the RRMS has the data from 2014, out of all the records in LIMS only the landslides that occurred after 2014 were selected. Different rainfall indices at the time of failure, such as cumulative rainfall for different time periods, soil water index, and working rainfall etc., will be evaluated by Principal Component Analysis to identify the significant indices to occurrence of a landslide. Then, considering the previous rainfall events at failure locations, the significant indices to predict a landslide will be evaluated by the Area Under Curve (AUC) of Receiver Operating Characteristic (ROC) curve obtained by Logistic Regression (LR) models. Finally, the probabilistic rainfall thresholds will be defined by two-dimensional or three-dimensional Bayesian approach using the most significant two or three rainfall indices.

Results and Working in Progress: Out of the 981 failure events recorded in LIMS by the end of 2022, 771 cases occurred on or after 2014. Then 303 cases were eliminated on the initial screening (based on failure type and data availability) (Figure 1). As the majority of the landslides are located in Kalu Ganga (123 Nos.) and Kelani Ganga (55 Nos.) catchment areas, they were selected for the study.

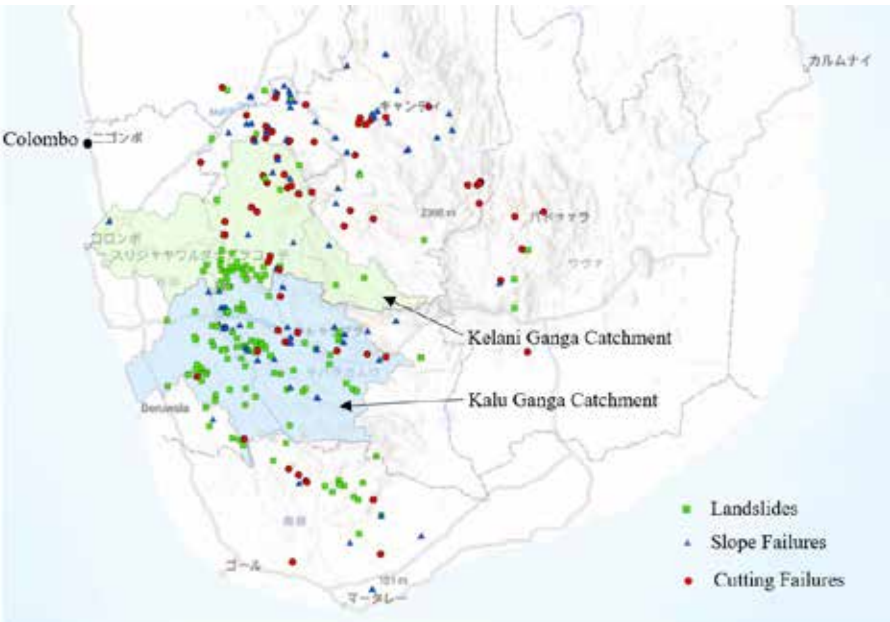

Fig. 1: Selected landslide by initial screening on catchment areas.

The analysis on the rainfall to select the better predictors for issuing early warnings and probabilistic threshold defining will be done using the 178 failure events in the selected regions.

FIRST EXPERIENCES FROM THE INFORM@RISK LANDSLIDE EARLY WARNING SYSTEM FOR INFORMAL SETTLEMENTS OPERATED IN MEDELLÍN COLOMBIA

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From 2019 to 2022 in course of the Inform@Risk research project a novel landslide early warning system (LEWS) designed specifically for informal settlements has been developed and implemented in the city of Medellin, Colombia. Since 2023 the system is operated and tested within a pilot project by the municipal risk management office (DAGRD) of Medellín.

The LEWS is based on five pillars: detailed analyses of the landslide risk, a dense geosensor network collecting information about triggering factors (rainfall, groundwater conditions) and precursory deformation, cloud-based data analysis methods, information dissemination via multiple channels including a smartphone app and extensive social integration efforts to create public awareness and preparedness. The system was developed in a participatory approach (living lab) including all actors (especially the inhabitants) in the development and implementation process.

The geosensor network installed in the 38 ha large project area “Bello Oriente” comprises about 120 wireless sensor nodes, 1,1 km of Continuous Shear Monitor (CSM) sensor lines, 3 data gateways and 4 up to 50 m deep instrumented boreholes. In large parts the geosensor network has been developed as an open-source project based on Internet of Things (IoT) technologies (wireless LoRa® communication and MEMS sensors) and low-cost production methods (3D-printing), which is believed to facilitate reproduction of the system in other areas. The data analysis methods, which partly are still in development, include sensor fusion methods, time series analyses and numerical landslide models to create spatially and temporally highly resolved and accurate landslide warnings. Many physical elements of the system have been integrated into the public space of the informal settlement in a practical way (e.g. as benches), making the system visible and useful for the public in their daily lives. Workshops, information campaigns (e.g. at schools) and emergency test drills further ensure the system is socially integrated and accepted.

Many lessons have been learned during the installation and first months of operation of the system, which have been compiled in an online documentation (www.informatrisk.com). The first analyses of the data acquired by the sensor system clearly demonstrates the potential of the system to identify landslides in their initial stages of development. During the ongoing pilot phase, the automatic data analysis and warning generation tools are being improved (trained) based on the collected data. Additionally, the integration of the warning system into the municipal risk management system is pursued.

The first experiences from the operation of the Inform@Risk LEWS are promising and the development towards a fully operational LEWS should be achieved by the end of the one-year pilot project. Due to the open-source components and comparably low cost the system should be replicable in many other regions worldwide.

NATIONAL-WIDE LANDSLIDE EARLY-WARNING SYSTEM IN THE REPUBLIC OF KOREA

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Introduction: Landslides are one of the most hazardous disasters in a forested mountain area in the Republic of Korea. Most of the landslides in Korea are shallow landslides induced by rainfall due to intense rainfall during summer, which is about 60% of annual precipitation. Recently, landslide hazards have become more significant because of climate change. To minimize the damage from landslides, National Institute of Forest Science (NIFoS) has studied and developed a national-wide early warning system for landslides. Here, we introduce the past research and the current state of the national-wide landslide early-warning system of the Republic of Korea.

Early stage (1980-2010): The development of rainfall threshold for landslide early warning have been conducted since 1980s. NIFoS collected rainfall data of 22 landslides where exact occurrence time had been known, and he suggested two-level intensity-duration rainfall thresholds; these contained rainfall intensity, daily rainfall amount, and cumulative rainfall amount. However, the thresholds suggested as national-wide regardless of spatial variability resulting relatively low early-warning accuracy.

Second stage (2010-current): In the late 2000s, NIFoS developed a new national-wide early-warning system using the TANK model, the so-called Korean Landslide Early-warning System (KLES). To overcome low accuracy due to the spatial variability, they defined nine subdivisions considering mean annual rainfall amount and geological property; parameters of TANKs have been optimized on each subdivision. Based on water contents in TANK storage (soil water index; SWI), KLES gives two-level alarms: caution and alert when SWI is 80% and 100%, respectively. In the early stage of KLES, it provided 1-hr landslide early-warning information. Recently, NIFoS has extended its 1-hr forecasting range to 12-hr using rainfall forecast data from KMA.

Future research: Although current KLES provides up to 12-hr early-warning information, a much longer forecasting range should be given to central and local governments for effective preparedness and evacuation. To service long-term early-warning information, NIFoS are improving the forecasting range of KLES up to 48-hr using 3-day weather forecast data from KMA. Moreover, we are conducting some studies to revise the parameters of TANKs and criteria for the preparedness phases.

IMPLEMENTATION OF PEOPLE-CENTERED APPROACH TO EARLY WARNING SYSTEM FOR LANDSLIDE IN THE PHILIPPINES

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Philippines is prone to natural hazards such as landslides because of its geology and climate. To reduce the landslide risk, the Dynaslope Project, under the Department of Science and Technology-Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS), pioneers the development and deployment of early warning system for deep-seated landslides (EWS-L) that is people-centered. The EWS-L is implemented in 52 at-risk communities across the country.

The EWS-L works by monitoring subsurface movement using the subsurface landslide sensors, surficial movement using surficial markers, which are measured regularly by the landslide early warning committee (LEWC), rainfall using rain gauges, earthquake, and observations of manifestations of ground movement. Data are stored in the database. Alert is generated based on the analysis of all the data. Then site-specific and timely early warning information are disseminated to stakeholders to aid them in preparing and responding to landslide risk.

The Dynaslope Project adheres to the people-centered EWS, an approach that actively involves the at-risk communities, facilitates public education, raises risk awareness, effectively disseminates warning, and ensures a constant state of preparedness. The Project also ensures that its activities cover all the elements of an effective EWS: (1) risk knowledge, (2) monitoring, analysis and warning services, (3) dissemination and communication, and (4) disaster response capability and following the cross-cutting themes of governance and institutional arrangement, community participation, gender, and cultural inclusivity. Lastly, the Project empowers stakeholders through community development through seminars and training related to the four elements and cross-cutting themes.

The Project continues to build and develop the capacities of its partner stakeholders, improve monitoring, analysis and warning, and innovate technology related to EWS-L. The goal is for the communities to be landslide-resilient through community-based EWS-L.

Keywords: early warning system for landslide, people-centered EWS, deep-seated landslide, Philippines

THE CATALAN EARLY WARNING SYSTEM FOR RAINFALL-INDUCED LANDSLIDES. NEW ONLINE PLATFORM AND EXPERIENCES GATHERED DURING THE TESTING PHASE

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Purpose: Rainfall-induced shallow slope failures and debris flows represent an important threat in Catalonia, similar as in other mountainous regions of the world. Early warning systems (EWS) act as a useful tool to predict the events and to reduce damages by improving the emergency actions. However, EWSs are difficult to transform into operational ones because of technical-scientific issues (uncertainty in rainfall-input, thresholds definition, etc.) and social-human aspects (communication to affected persons, meanings of warning level, etc.).

Methods: In the last decade, the general methodology for a Catalan landslide EWS has been developed and continuously improved (Berenguer et al. 2015; Palau et al. 2022). It combines information of landslide susceptibility and real-time rainfall measurements by radar and rain gauges. Every 30 minutes, the system emits a warning, which is defined by four different levels (from very low to high). The mapping units for the visualization of the warning levels are first- and second order basins, while the calculations are performed at pixel-size with a resolution of 30 meters.

Results: Recent advances of the landslide EWS include the online platform that serves not only as a visualization tool of the warning maps, but also as an instrument to consult inventory data of past landslides or both rainfall and warning level time-series at specific locations. An example of the present design of the platform is illustrated in Figure 1. The platform and the EWS are presently undergoing a testing phase, which has the aim to check several operational and technical aspects. First results showed that the new platform strongly facilitates the work of the different users from UPC and ICGC to easily access, check and interpret the warning maps. Regarding the performance of the EWS, past landslide episodes were analyzed and preliminary results showed satisfactory warning issues. Nevertheless, the rainfall thresholds might be adapted or the incorporation of soil moisture should be considered in order to improve the accuracy. In addition, an improvement of the susceptibility map, which is currently based on a fuzzy-logic approach, would probably conduct to better and more precise warning maps.

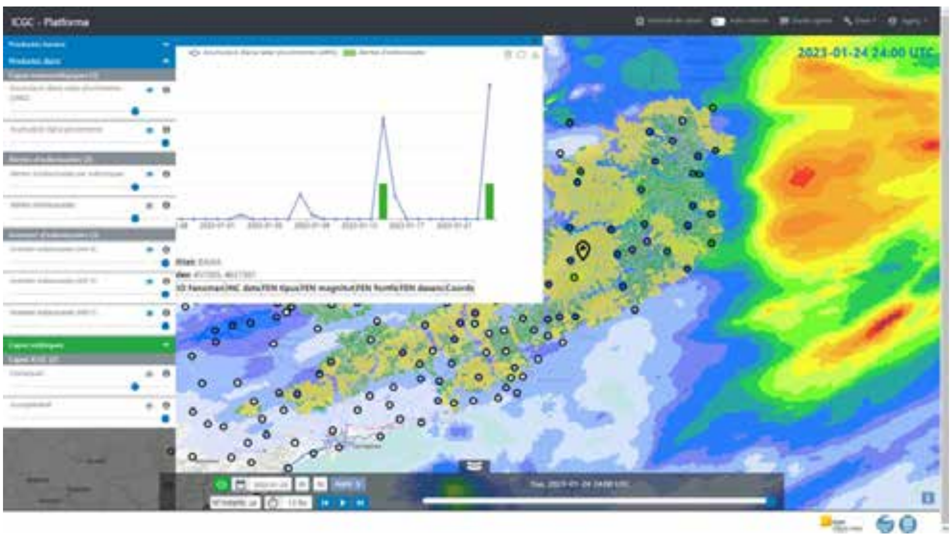

Fig. 1: Screen-shot of the EWS platform.

Conclusions: The implementation of an EWS for landslides in Catalonia is a work in progress, but the gathered experiences show that it's a useful tool for landslide mitigation that should play an important role in the future.

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END-TO-END EVALUATION OF TERRITORIAL EARLY WARNING SYSTEMS: AN ITALIAN CASE STUDY

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Purpose: The contribution addresses, from a conceptual point of view, the complex issue of evaluating the performance of warning systems that are operating over large areas to cope with the risk posed by landslides induced by extreme weather events.

Methods: The reference terminology and characterization adopted in this study for landslide warning systems operating over large areas, herein called territorial landslide early warning systems (Te-LEWS), is provided by Piciullo et al. (2019). All the many elements comprising an operational early warning system for weather-induced landslides must be considered to evaluate its performance (Calvello, 2017). To this aim, this contribution adapts to Te-LEWS the framework that Golding (2022) has proposed to address the different components of a warning chain, defined with the aim of building greater resilience to weather-induced hazards in the design and implementation of warning systems. In particular, the "valleys of death concept" of the Warnings Value Chain is herein adopted, using the approach developed in Hoffman et al (2023). This study is being carried out within the Horizon Europe project "The HuT: The Human-Tech Nexus - Building a Safe Haven to cope with Climate Extremes" (https://thehut-nexus.eu/).

Results: The main result of this study is the definition of a pilot end-to-end evaluation procedure specifically assessing the performance of Te-LEWS. The procedure comprises a questionnaire addressing in detail all the elements of the warnings value chain, to be filled for each analyzed warning event, and an assessment form, which synthetically rates the value chain elements considering the responses provided in the questionnaire. The preliminary validation of the proposed procedure has been carried out using data from a warning zone of the operational system deployed in Campania region (Italy), comprising 110 municipalities over a territory of 1,620 km2. In particular, a series of significant regional warning events, only in part associated with the occurrence of landslide events, have been analyzed. The assessment has been conducted in relation to two different scales of analysis: over the entire warning area; considering the territory of a single municipality.

Conclusions: The effectiveness of a Te-LEWS depends on a series of elements and actors that must be thoroughly and objectively evaluated, whenever a warning is issued, to create a context for risk management responsibility along the entire warning chain.

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DEVELOPMENT AND APPLICATION OF AN INNOVATIVE METHODOLOGY FOR SPATIO-TEMPORAL PREDICTION OF LANDSLIDES THOUGH A MACHINE LEARNING TECHNIQUE

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Machine learning techniques are commonly used for landslide susceptibility assessment. However, their application for spatiotemporal landslides forecasting remains widely unexplored. The aim of this study is to develop an innovative method for spatio-temporal landslide forecasting using a machine learning technique, namely, Random Forest (RF). A comprehensive landslide inventory was compiled in a study area in Norway. A filter of the landslide entries has been carried out selecting shallow landslides and debris flows only. RF, among its advantages, allows the calculation of the Out-of-Bag Error (OOBE) and depicts the Partial Dependence Plots (PDPs), two indices that express the weight of an input variable affecting the model forecasts, and are used in this study to verify if the results are in line with our knowledge of the physics of the triggering of the inventoried landslides.

The proposed methodology is based on the identification of landslide and non-landslide events over space and time. The following dynamic variables have been included in the analysis: i) the cumulative rainfall at several time steps (from 1 to 30 days); ii) the month of the landslide and non-landslide events, considered as a categorical type, to express the seasonal variability of rainfall; iii) the average daily temperature and iv) the snowmelt; the last two variables were chosen to investigate their influence in the triggering of landslides in boreal environments. In addition, a landslide susceptibility index (LSI) was inserted as static input data, derived from the classic application of the RF model, with the most common static parameters used in the literature. LSI was exploited to directly compare the influence of dynamic variables and of predisposition of the study area in landslides triggering.

For training and test phases, the number of non-landslide events is considered equal to the number of landslide events, or a multiple of it, allowing to investigate the effect of different degree of imbalance between non-landslide and landslide event databases on the model outcome. The obtained models were then reapplied in back analysis on the study area before, during, and after specific landslide events, in order to obtain a landslide probability map for each case.

Encouraging results were achieved: it was verified the greatest importance of short-term and intense rainfall in the triggering of shallow landslides and debris flow, as well as of their seasonal variability and of predisposing characteristics of the study area. The degree of imbalance of the database results a control factor for model calibration and performance optimization.

In conclusion, the applicability of the RF model for spatio-temporal prediction of landslides using the proposed methodology has been demonstrated, representing a promising starting point in the perspective of a more complete landslide risk analysis through machine learning techniques and for early warning system purposes.

MOVING TOWARDS NEAR-REAL TIME FORECASTING OF RAINFALL-INDUCED LANDSLIDES

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Purpose: The increase in the frequency of extreme events results in an increased frequency of landslide events. Rapidly growing developments of infrastructure eventually extend to terrains carrying signals of unstable slope conditions which results in hazardous conditions for the residing communities. Taking the steps to address this problem, multiple research efforts have been made to aid in developing a Landslide Early Warning System (LEWS). One of the most recent and large-scale real-time model for this purpose is the second version of the Landslide Hazard Assessment of Situational Awareness (LHASA). This tool is based on a machine learning core and ultimately visualises Rainfall-Induced Landslides (RIL) occurrence probabilities on a global scale. The probabilities vary both in space and time as a function of static terrain characteristics and dynamic rainfall ones. However, the interaction of rainfall with the terrain in the context of orography is not fully utilised in methods that independently combine these two, thus neglecting the rainfall-terrain interaction.

Methods: This work attempts to dynamically include the interaction of rainfall and terrain properties using a Generalized Additive Model (GAM) in a Bayesian framework. Differently from LHASA, a Bayesian GAM allows to interpret the model results and to provide uncertainty estimates around the mean prediction. To do so, we integrated rainfall information from satellite-based products, identifying the best antecedent rainfall window through a variable selection step. This allows moving away from the common use of rainfall-thresholds and towards the use of probability thresholds behind the definition of the issued warnings. Thanks to a rich multi-temporal inventory available in the literature for the Lower Mekong Region (LMR), we complemented the analyses with a suite of spatio-temporal cross-validations, including a transferability test far away from the training area.

Results: The output of multi-fold validation techniques categorised the model's performances as good to excellent overall, with some localised exceptions. Ultimately, a prototype of alert system was also created within Google Earth Engine where a web-based visualization platform is accessible for anyone to visualize the mean prediction on a daily basis. However, the use of Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) still limits the ability to use the tool in near real time or as a forecasting base.

Conclusions: The proposed robust modelling framework holds much promise for adapting to rainfall prediction data. In turn this would allow to make use of weather forecast into landslide forecast through an explainable model equipped with uncertainty estimations and a visualization platform that could be highly useful to support disaster risk management practices.

INTEGRATION OF ANTECEDENT RAINFALL TO IMPROVE THE PERFORMANE OF 3D THRESHOLDS FOR LANDSLIDE EARLY WARNING SYSTEM: A CASE STUDY IN WANZHOU DISTRICT, CHINA

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Purpose: Landslides triggered by heavy rainfall are increasing due to climate change and cause severe damage to human communities in mountainous regions. For a better prediction of such events, the rainfall thresholds are employed as the critical criteria and widely engaged in landslide early warning systems (LEWS) at different scales. The empirical and probabilistic thresholds obtained from specific rainfall events are easy to use but ignore the physical background of slope instability, leading to a relatively lower performance with high false alarms.

Methods: This study attempts to improve the conventional thresholds to three dimensions (3D) by considering the antecedent rainfall and its effective infiltration. We give insight into the Wanzhou District in southwestern China, which suffered from fatal landslides over the past years, but no rainfall thresholds have been developed for LEWS. A total of 783 landslide records and hourly data from 78 rainfall gauges spanning 2014 to 2020 were used for statistical analysis. The automated algorithm Massive Cumulative Brisk Analyzer (MaCumBA) was utilized to establish the intensity–duration (I–D) threshold. To extend the thresholdS from plane to spatial, the mean effective areal rainfall (MEAR), representing the average rainfall amount infiltrated into the ground, was introduced as the third dimension. The values of MEAR were calculated according to different time periods (7, 10, 15, and 30 days) and accounted for exponential decay. The improved approach was calibrated individually for 11 alert zones and then validated and compared with classical I–D thresholds.

Results: The result shows that the accuracy of the I–D thresholds ranges from 76% to 91%, while the number of false detections is high with low precision (from 11% to 39%). The participation of MEAR satisfies this shortcoming with a consistent decrease in false alarms (from 24% to 95%). Moreover, compared with the 3D thresholds without reduction, the application of the effective rainfall model allows the updated method to identify more false alarms (from 1% to 12%).

Conclusions: The updated 3D thresholds could reflect the coupling effect from triggering rainfall and the antecedent hydrological process. With the consideration of MEAR, the proposed method give a promising perspective for developing an operational LEWS with good performance and robustness in the study area.

TOWARDS A NATIONAL LANDSLIDE EARLY WARNING SYSTEM FOR SWITZERLAND: A PILOT STUDY TO ASSESS THE USE OF SOIL WETNESS INFORMATION AND PHYSICALLY-BASED MODELLING

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Purpose: A new national Landslide Early Warning System (LEWS) for Switzerland is currently under development and will be launched in 2025. To assess the potential of the methods under consideration and to verify the warning system at regional scale, a pilot study has been conducted in the Napf-region, a hilly semi-forested area (186 km2) where numerous storm-induced landslides have been documented in recent years. One cornerstone of the LEWS in the pilot study is the in-situ soil wetness monitoring at six locations distributed across the region, representing the variability with respect to altitude, inclination, and soil conditions. Here, we demonstrate how these soil wetness measurements, together with a numerical soil hydro-mechanical landslide model, have been used to add value to the upcoming national LEWS.

Methods: Two in-situ soil wetness measurement sites were installed in 2019, and four additional in 2021 to record volumetric soil water content and soil water potential in four depths at a time resolution of 10 minutes. A tailored visualization tool provides a quick overview of the current soil wetness conditions and allows to compare selected soil wetness indicators with previous years. This information was used as input and verification data for a numerical hydro-mechanical landslide model, STEP-TRAMM (available at https://emeritus.step.ethz.ch/step-tramm.html). The model depicts the landscape as a composite of interconnected (non-layered) hexagonal soil columns, computes the spatially distributed soil depth, and accounts for spatially variable rainfall, soil properties, topography, and forest distribution. It calculates the dynamics of soil water flow and the progressive material failures culminating to hazardous landslides. In this pilot study, the model was applied to reproduce past storm events with and without observed landslides. By varying initial conditions and mechanical and hydrological soil properties, we assessed the appropriate parameter range and the sensitivity of the model.

Results: Profile-integrated soil wetness data from the six monitoring sites consistently illustrated the seasonal variability and thus provided useful indications of antecedent (initial) conditions of storm events to be simulated by the numerical model. For three storm events in 2021 and 2022, the simulated soil water content captured the range of the observations and reflected different soil types and topographical locations reasonably well. The simulation of landslide triggering was sensitive to the selection of soil type, initial soil saturation, and spatial resolution (i.e., the soil cohesion value had to be systematically adjusted within a justifiable empirical range as function of grid size).

Conclusions: We could demonstrate that the model is able to reproduce past storm events at the scale of the Napf-region in a timely manner. The soil wetness monitoring helped narrowing down the parameter space of the numerical model and confirmed the adequacy of the (pragmatic) model representation of soil/slope wetting and draining. For a future LEWS, physically-based models have a considerable potential to complement established statistical approaches for assessing warning levels and identifying specific situations and locations at risk.

SESSION 1.3

CASCADING MULTI-HAZARD RISKS: SUBMARINE LANDSLIDES, TSUNAMIS, AND IMPACTS ON INFRASTRUCTURES (part II)

THE 1977 GIOIA TAURO TSUNAMIGENIC LANDSLIDE (ITALY) AS AN EXAMPLE OF CASCADING MULTI-HAZARD RISK

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Submarine landslides are considered a main geohazard for coastal and offshore infrastructures, because they can directly impact them during their development (i.e., retrogressive failures affecting coastal areas or cable breaks due to the related sedimentary gravity flows) or generate local but devastating tsunami waves. In this latter case, submarine landslides, tsunamis, and impacts on infrastructures are a classic example of cascading multi-hazard risks. In this study, we present a reappraisal of the tsunamigenic landslide occurred on 12th July 1977 at the head of the Gioia Tauro Canyon (Southern Italy), when tsunami waves up to 5 meters high hit the coastline during the construction of the port of Gioia Tauro, causing severe structure damages. The event is still poorly understood because of lack of detailed data before the landslide and paucity of scientific studies afterwards. In this study we integrated unpublished technical reports realized before and after the event with morpho-bathymetric and seismic data to achieve a better comprehension of the event dynamics.

The reconstructed scenario shows that the 1977 slope failure was favored both by the presence of a steep submarine depositional terrace (SDT) within the canyon head, made up of prograding sand and gravel as well as by the dumping of a large amount of sediments, derived from port excavation, within the canyon head and above the SDT. This produced a partial infilling of the canyon head and dramatically increased the aggradation/progradation of the SDT, until a slope failure occurred. The landslide caused both the collapse of dumped sediments, but also the retrogressive failure of a ~2km stripe of SDT on the neighboring coastline, indicating again the proneness of this depositional body to fail. This retrogressive mechanism has likely played a key role in tsunami propagation and damages all along the western pier of the harbor under construction at that time. It is noteworthy that another tsunamigenic landslide occurred two years later at the head of the Var Canyon during the construction of a new Nice harbor extension, close to the Nice international airport, generating severe damages and tens of casualties.

SUBMARINE LANDSLIDE HAZARD IN THE ALBORAN SEA

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Purpose: In the southern margin of the Alboran Sea, where the convergence between Eurasia and Nubia is accommodated, several submarine landslides (0.01 to 15 km^3) are stacked within the last million year of sedimentary (contouritic) cover. Historical earthquake records suggest that seismicity is mostly triggered by strike-slip faults with little or no vertical throw preventing significant tsunami formation. This points to submarine landslides as the main potential source of tsunamis. In order to provide a regional analysis of the tsunamigenic hazard of submarine landslides, two projects were funded by French research agencies: (i) the ANR Albamar project, focused on the causal factors of submarine landslides and (ii) the CNRS-IRD Alarm project, addressing tsunami hazards and risks in the Alboran basin. The purpose of this communication is to present major results of these two projects.

Methods: On the one hand, the analysis of the causal factors integrates a submarine landslide dataset (compiled from geophysical data) and oxygen isotope chronostratigraphy and mechanical characterization of contourites thanks to sediment cores and in situ geotechnical (piezocone) data. On the other hand, the run-up of different landslide (volume) scenarios has been simulated using the SHALTOP code and then used as a source of tsunami using the hydrostatic 3D Navier-Stokes code Freshkiss3d. Moreover, the statistical extreme value analysis is applied and the occurrence of “severe” landslides (with a tsunamigenic potential) addressed.

Results: Ages of the most recent submarine landslides investigated (with a seabed expression and volumes between 0.01-0.5 km^3) are between 11-12 kyrs, which suggests a simultaneous trigger. According to the mechanical characterization undertaken, different failure scenarios, including earthquake loading and slope erosion due to water masses oscillations is proposed. Tsunami simulations suggest that landslide < 1 km^3 do not exceed 1m of maximum water height nearshore. According to the extreme values analysis, the landslide volume considered as an extreme threshold is 0.5 km^3. Our study confirms that extreme landslides with volumes higher than this threshold have occurred (with volumes up to 15 km^3) during the last million year and that their tsunamigenic potential may imply devastating maximum wave heights of several meters. Nonetheless, the probability of occurrence of extreme events (> 0.5 km^3) is relatively low (e.g. 5% for a 5 km^3 landslide).

Conclusions: The work carried out within the framework of the Albamar and Alarm projects contribute to better address the potential tsunami hazard linked to submarine landslides. The question about the probability of occurrence in a temporal scale remains partially answered. Ongoing chronostratigraphic analyses will help to improve this in the future.

LARGE-SCALE GRAVITATIONAL COLLAPSE IN THE CROTONE PROVINCE (CENTRAL MEDITERRANEAN)

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Purpose: The purpose of this study is to provide a better understanding of the scale, timing and driving mechanisms of current activity of a large scale gravitational collapse in the Mid-Miocene to Quaternary Crotone Basin, a forearc depocenter located on the Ionian side of the Calabrian Arc (southern Italy) and developed under alternating episodes of rollback and subduction of the Ionian lithosphere during the Tyrrhenian back-arc basin oceanization.

Methods: Integrated approach of seismic reflection, well and field data, together with literature information. Seismic interpretation consisted of the recognition of key reflectors (generally corresponding to lithological changes and unconformities) bounding seismic units characterized by different seismic facies and/or configuration patterns, reflector terminations, depth and thickness. Unconformities of regional significance were identified on seismic reflection profiles and calibrated on the basis of well data and literature information.

Results: This study have revealed that almost all the Crotone province lies above a buried megaslide that involves an up to 1600 km thick sedimentary succession and extents for an area of ca. 1800 km2. This megaslide is made up of an onshore updip extensional domain, which is connected southward to an offshore downdip compressional domain through a buried detachment surface over a Messinian halite layer. The updip extensional domain coincides with a curved seaward-dipping fault system outcropping along the NW part of the Crotone Basin, while the downdip compressional domain is inferred to correspond to a prominent submerged morphological high, the so-called Crotone Swell. The landmass, which involves the Messinian-Pleistocene deposits, has started to slide since the Zanclean, and experienced a paroxysmal phase between Late Zanclean and Early Piacenzian. This episode is related to Middle Pliocene contractional/transpressional tectonics in the context of temporary collision of the NE Calabrian Arc with the adjacent Apulian margin. The paroxysmal episode of the megaslide was followed by a phase of inactivity during the Calabrian. This phase is linked to the SE-ward migration of the Calabrian Arc and Ionian lithosphere subduction, concomitant with the opening of the Marsili sub-basin in the Tyrrhenian back-arc area and with the rapid drowning of the Crotone Basin. The megaslide underwent a second reactivation since the Middle Pleistocene due to regional uplift, and seems to be restricted to the offshore sector, the Crotone peninsula and probably the eastern coastal area.

Conclusions: The Mid-Miocene to Quaternary Crotone Basin has been affecting by large-scale gravitational collapse since the Pliocene:
- The megasliding initiated in the Zanclean, as demonstrated by the development of syn-sedimentary listric fault in the headwall region;
- The megasliding underwent a high-magnitude phase between the Late-Zanclean and the Early Piacenzian, as documented by a scar surface cutting through the mid-Pliocene unconformity and overlain by chaotic deposits, in turn sealed by Piacenzian and younger sediments;
- The megasliding experienced a temporary pause of paucity, as evidenced by a direct contact between the Calabrian and Zanclean sediments, and reactivated during the middle Pleistocene as demonstrated by the fact that the basal shear surface crosscut the seafloor and the Pleistocene terrace in the Crotone peninsula.

AN APPROACH TOWARDS SUSCEPTIBILITY ANALYSIS FOR TSUNAMIGENIC LANDSLIDES IN INDONESIA

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Purpose: Landslide triggered tsunamis have come into focus of scientific research in recent years. This is due to catastrophic events such as the 2018 tsunami in Palu, Indonesia, which inundated the coastline in Palu Bay with unexpectedly high waves as a result of an earthquake and coseismically triggered landslides, causing nearly 2,000 fatalities. Landslides can generate enormously high tsunami waves up to several tens of meters. However, these are very local phenomena and the generated waves usually do not propagate further than 100 km within the radius of the triggering landslide. The areas that are in the immediate vicinity of the landslide are usually the most affected. Due to the very short time interval between the initiation of the waves and their arrival at the coast, early warning of such events is not possible so far.

Methods: In this study we conduct a susceptibility analysis for nearshore and submarine landslides that have a high potential for triggering destructive tsunami waves. A major challenge is the low data availability. In particular, high-resolution bathymetric data to evaluate submarine slope morphology is not available on large scales. Therefore, a heuristic model is chosen for the susceptibility analysis, which is weighted and calibrated using known historical case studies. The analysis is conducted for several pilot areas in Indonesia. The analysis consists of two steps. First, landslide susceptibility is investigated for areas within a distance of two kilometers from the coastline. Geologic, tectonic, morphologic and hydrologic parameters are considered for the analysis. In a second step, coastal sections are investigated where the generation of especially high tsunami waves is likely. For this, morphological seafloor properties and coastline geometry will be considered.

Results: First results show a high correlation of landslides generated during the 2018 Palu earthquake with the size and steepness of catchment areas of rivers entering the ocean. Those parameters strongly affect the sediment freight that is transported into the ocean. High sedimentation rates in river mouths might lead to the formation of unconsolidated sediments, which are highly susceptible to landslides. This correlation, amongst others, is going to be further analyzed.

Conclusions: The results of this susceptibility mapping can help local officials educate the population of affected areas about the hazards posed by this particular form of tsunami. For example, in affected areas, even low-magnitude earthquakes that are not expected to produce seismically induced tsunamis can trigger submarine or subaerial landslides, which generate waves. In endangered areas, it may therefore make sense to adapt tsunami evacuation strategies not only to seismically triggered waves, but to landslide-induced tsunamis as well. Susceptibility mapping for possibly tsunamigenic landslides remains a complex problem, especially because of data scarcity for submarine slopes. In a country like Indonesia, which is particularly prone to tsunamis due to high seismic activity and thousands of kilometers of coastline, it is an important attempt to delineate the areas where particularly high and destructive tsunami waves can be generated due to landslides. The present study is a first step towards tackling this complex problem.

TSUNAMIGENIC FLANK FAILURE ASSESSMENT OF CUMBRE VIEJA VOLCANO, LA PALMA, AND ASSOCIATED HAZARD FOR MOROCCO AND THE NORTH ATLANTIC BASIN

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Purpose: Without extensive surveying and analysis, predicting volcano flank collapse is associated with significant uncertainty. Geological evidence and previous research have identified that Cumbre Vieja Volcano, a constituent part of the Canary Islands, carries a high risk of catastrophic collapse during a future eruption. The Canary Islands are also in a unique position to be capable of producing tsunamis that pose a risk to the entire Atlantic basin, particularly the nearby Atlantic coast of Morocco.

Methods: We identify possible ranges for landslide parameters (such as depth, start/end point, width, length, volume, etc.) and, using a random sampling strategy to create a database of possible flank failure scenarios. Using the Cornell Multi-Grid Coupled Tsunami (COMCOT) model to simulate each of these scenarios from landslide and subsequent tsunami generation, through to propagation and runup along Agadir Bay, Morocco, and the wider trans-oceanic propagation to the western coast of the United States. This study will make use of virtual coastal surface elevation gauges and inundation extents as quantities of interest to measure tsunami hazards, and outputs from all scenarios will be compiled to provide a probabilistic assessment of the tsunami impact across the study area.

Results: From these results, the outputs of this study will provide insight into the most probable maximum wave heights and inundation extents, as well as provide a set of credible worst-case scenario events for different regions across the Atlantic basin.

Conclusions: We anticipate that these results will allow key stakeholders such as emergency managers, city planners, local authorities of countries around the Atlantic basin to better understand the tsunami risks posed by tsunamigenic flank collapse from Cumbre Vieja and provide evidence of the importance of including landsliding on La Palma, and other islands within the archipelago, in their tsunami hazard assessments and design of preventative measures.

ASSESSMENT OF CURRENT AND FUTURE MULTI-RISK INTERACTIONS AND CASCADING IMPACTS ACROSS EUROPE: A CASE STUDY IN OSLO, NORWAY

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Natural hazards are events caused by nature, which can cause damage or loss of life, infrastructure and property. While the direct impacts of natural disasters are well understood, the channels through which these shocks spread to non-affected regions are not solved yet. (Naqvi A et al. 2021). Cascading effects are secondary consequences that can occur following a natural hazard event and negatively impact regions by exacerbating socioeconomic vulnerabilities. It is important, therefore the planning of mitigation strategy through preparation and implementation of prevention measures. To this purpose, this paper shows an innovative resilience-based, service-oriented and people-centered approach developed in the European project "Multi-hazard and risk-informed system for Enhanced local and regional Disaster risk management (MEDiate)". MEDiate aims to develop a decision support system (DSS) for disaster risk management, considering multiple and interacting natural hazards and cascading impacts. The aim will be to implement the models within an accessible and user-friendly computer system so that end users can understand, quantify, and visualize future multi-hazard situations. This innovative methodology, due to its scalability and replicability, will be applied in different geological contexts, at regional, national and international scales. This work will focus on the case study of the Alna district in Oslo (Norway). This is a high-profile urban area with substantial residential, commercial and industrial structures and facilities. In particular, the Alnabru terminal in the area is Norway's largest freight terminal for road and rail and the very hub of Norwegian freight transport by train. The district is exposed to multiple hazards (landslides, flood, and fire), in particular to quick clay landslides. Quick clay is a marine clay sediment where the salt that binds the clay together has been washed away over time. Thus, the structure becomes unstable and increased point loads or erosion of waterways can trigger landslides. In case of a landslide, the quick clay becomes liquefied, and major material damage and danger to life can occur. This study will apply the emerging methodology in a multi-hazard scenario to evaluate the physical impact on the built environment and assess the social impacts on the population and businesses. Especially, we will evaluate the cascading effect of the physical and social impacts due to the disruption of the transport network. Finally, it will be demonstrated how cascades propagate across domains of interest and their implications for governance by providing sufficient flexibility that will allow different decision makers to tailor analyses and visualizations in line with their specific priorities.

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SESSION 6.4

MACHINE LEARNING APPLICATIONS IN LANDSLIDE SCIENCE (part II)

FROM VOICE RECOGNITION TO LANDSLIDE TRIGGERING: ASSESSING THE POTENTIAL USE OF ARTIFICIAL INTELLIGENCE TO IDENTIFY LANDSLIDE INITIATION CONDITIONS

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Purpose: Landslide is a well-known natural hazard, responsible each year for a high number of casualties and economic losses. Scientific community is taking huge efforts for landslide risk reduction and one of the most popular strategies is the setup of early warning systems (EWS). Local EWS can take advantage of monitoring data or physical modeling, while regional warning system usually rely on statistical or empirical approaches aimed at the identification of the landslide triggering conditions. These approaches are easy to implement but usually suffer of low sensitivity or specificity, as well as of low spatial resolution. In the last years artificial intelligence made its way into the field of landslide hazard assessment, showing its potential in reducing some uncertainties. Artificial Intelligence is now mainly used for landslide hazard assessments, for landslide mapping and detection, while it is still scarcely used for temporal landslide forecasting. In this work we tested the use of voice recognition methods to identify the “rainfall signature” associated with the initiation of rainfall induced landslides, to verify its potential application for landslide forecasting.

Methods: Hourly rainfall time series have been used as input data of the model and labeled according to their association with the presence of absence of landslide events. Long short-term model was used to recognize the pattern of rainfall time series and to associate them with the occurrence or absence of landslides. Since this work represents the first attempt of this kind of approach, several association rules (rain gauge-landslide) and different model configuration have been tested, to identify the best performing setting without overfitting issues. The model was tested in an area were previous study about the rainfall condition associated with the initiation of landslides exist, so as a benchmark was available to assess the quality of the results. The model was trained using over 1000 rainfall induced landslides distributed over 10 years and a same number of rain events without landslides; the data were divided into training, validation and test sets and randomly shuffled several times, to assess the strength of the model.

Results: Results showed that the accuracy of the model is highly dependent on its initial set up and that it can vary from 60% up to over 90%, with a false positive rate up to less than 5%. Computational time for the application the learning model was evaluated using a standard desktop PC and it resulted to be suitable for its implementation in a landslide warning system.

Conclusions: Even if this is a first attempt of its kind the early results showed that its predictive capabilities are sensibly higher than statistical or empirical approached. Some aspects need to be better addressed, as the refinement of the association rules and the bettering of the spatial resolution of the forecast, but there is the potential for its implementation in an early warning system.

SOCIAL MEDIA FOR LANDSLIDE EVENT DETECTION AND SITUATIONAL AWARENESS

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Purpose: With the advancements in the usage of social media by common people, detecting, communicating, and managing disastrous events like landslides have become more promising than before. Recently technological developments such as machine learning, natural language processing, have facilitated social media data collection, data integration, combined interpretation from multiple platforms, with varying spatial and temporal resolutions. However, it can be challenging to extract the most relevant information, due to the vast amount of data. Also it is tedious to search for and determine the availability of valid and important information. At the present stage, the government officials are unable to decide when to take an event seriously because information is not spatially and temporally quantified and it is constantly streaming in.

Methods: Here, we discuss how Machine learning is used for efficiently summarizing the precursors of landslide disaster events such as rain, flood, and landslides and early detecting the possibilities of landslide or flood events. We have carried out this approach in the following ways. (i) Collecting related tweets using keywords and hashtags: To collect disaster-related tweets, a developer account and Twitter libraries, also known as twitter wrappers, are used to collect tweets programmatically. Specific keywords such as 'Rain', 'Heavy Rain', 'Flood', 'Landslide', 'Strom', 'Mudslide', 'Slope failure', 'Rockfall' etc are used to collect tweets related to these keywords. (ii) Analyzing historical data & setting thresholds: Past case studies related to landslide events are studied to identify patterns and trends that are followed before, during and after a disaster. This study helps to identify the types of language, sentiment, and keywords associated with past landslide events and is also used to set thresholds for detecting future events. Thresholds are set to ensure detecting an event ahead of time. These thresholds are set based on the volume of posts, trend, order in which the tweets are increasing, and the date when the incident happened.

Results: Event detection: If the number of posts exceeds this threshold, it may indicate that a landslide event has occurred or is likely to occur in that area. Similarly, thresholds can be set based on sentiment analysis, with a higher number of negative sentiment posts indicating a greater likelihood of a landslide event. Social media has been used in natural disaster management to strengthen situational awareness and improve emergency response. Situational awareness: Common public can be informed of situational notifications based on the data that is collected. This information will be more useful for crisis response groups who can use social media as a platform to interact with the public in disaster circumstances. Human-centric information from social media helps understanding the ground reality, and in a variety of management tasks throughout all disaster stages, including mitigation, preparedness, response, and recovery, to lessen the impact of disasters.

Conclusions: Natural hazard precursors, like "heavy rainfall before a landslide or a flood disaster," are more frequently reported in social media; if these precursor data can be collated and evaluated efficiently through proper methodologies, then the occurrence of natural hazard can be anticipated and better handled.

UNCOVERING LANDSLIDE FAILURE MECHANISMS USING ADVANCED 3D TOPOLOGICAL DATA ANALYSIS

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Purpose: Landslides are hazardous mass movements that can be induced by various factors such as lithology, morphology, soil properties, hydrology, and seismicity. To mitigate their impacts, we need to understand their failure mechanisms in diverse contexts and scenarios as this would allow us to improve existing predictive models that generally group different landslide modes into one category, thereby inducing bias and uncertainties. In our study, we aim to determine the likely failure mechanisms that occurred due to an event and attempt at classifying both historical and event-based inventories to identify the failures.

Methods: We employ a mathematical framework called Topological Data Analyses (TDA) that decodes the geometrical and topological features of landslides in 3D based on parameters such as slope gradient, landform characteristics, and kinematic propagation. The TDA is coupled with machine learning as a data-driven approach to learn topological properties of distinct failure modes. This enables us to distinguish different modes of failures such as slides (where the rupture slides along a plane), flow-like (where soil deforms as a viscous material), rockfall (where rocks detach from a cliff), and complex (where multiple modes coexist). The approach is employed on the Italian data set using ~250,000 landslides (covering the entire nation) from the IFFI catalogue and the Pacific Northwest region of the US with over 50,000 landslides. Both regions are geographically very distinct and hence, we presume to capture diverse modes of failure conditions.

Results: Our first results are encouraging, with over 95% accuracy for each failure mode in the Italian environment and over 80% accuracy for each mode in the Pacific Northwest area of the United States. We also showed that topological qualities provide more information in distinguishing between failures and that topology conveys complicated landslide information inherent in their morphologies better than standard geometric properties like area, perimeter, ellipticity, and so on. Additionally, it was found that when implementing this approach, a minimal amount of data (~500-900 samples) was sufficient to attain over 80% prediction capabilities.

Conclusions: In this study, we offer an unique approach to determining the processes of landslide failures by leveraging topological features. Rather than relying solely on classical geometrical properties, we examine the topology of the landslides with machine learning. We can differentiate diverse landslide processes with more accuracy than existing approaches by using topology as a descriptor. Our findings suggest the possibility of discovering common topological properties, which might lead to a better understanding of each failure process and the development of transferable and scalable models for identifying landslide failure types. Our findings have significant implications for lowering bias and uncertainty in predictive models as well as enhancing landslide forecasting in landslide-prone locations.

SLOPE FAILURE PREDICTION USING CONVOLUTIONAL NEURAL NETWORK

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Purpose: An evaluation of the safety factor and the failure surface of a slope, so-called slope stability analysis, is essential in geotechnical engineering design and analysis. Slope safety can be evaluated by limit equilibrium and finite element methods, etc. Due to spatial variability in soil properties, the random finite element method incorporating the random field concept has been introduced to evaluate slope uncertainty and reliability.

Methods: The random finite element method requires a quantitative evaluation of a slope failure probability, which is time-consuming. Therefore, use of machine learning and deep learning techniques, a path to achieving artificial intelligence, can be an alternative way to predict slope failure quickly. Among these methods, convolutional neural networks (CNNs) have become popular for image analyses because they can extract information directly from 2D shapes, such as crack damage detection, bearing capacity prediction of shallow strip footings, and slope stability analysis. A CNN model that considers the spatial relationships of input data was recently shown to be a suitable method for addressing random field problems. Comparatively to the traditional finite element method, it effectively facilitates the computation time.

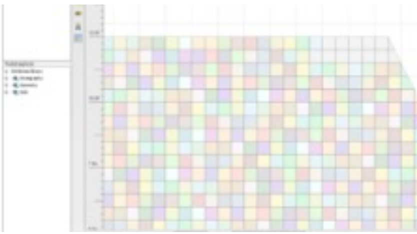

Fig. 1: Random finite element slope stability analysis.

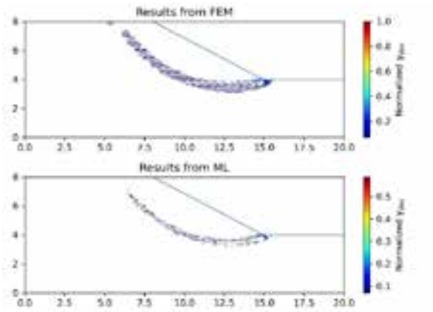

Fig. 2: Training results of factors of safety of 30o slopes.

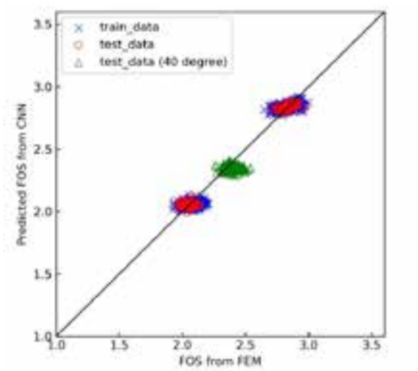

Fig. 3: Factors of safety of slopes analyzed and predicted.

Results: In this study, a CNN model is pre-trained by feeding into simulation results with slopes with inclinations of 30 and 50 degrees conducted by the random finite element method.

Conclusions: The results show that the proposed CNN model can predict the slope failure and safety factor under a slope with an inclination of 40 degrees. However, the prediction of failure surface requires more work to enhance its accuracy.

MACHINE LEARNING-BASED PREDICTION OF MUDSTONE SOIL STRENGTH TREATED WITH SUGARCANE PRESS MUD: A CASE STUDY

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Purpose: Mudstone soils (MS) are problematic for their susceptibility to geological damage, including landslides and erosion. To gain a better understanding and address these challenges, numerous studies have been conducted on this topic, including investigations into various treatment methods (Hung et al. 2018; Lin et al. 2019; Ghadr et al. 2022; Gumanta et al. 2023). Nonetheless, there is still a need to improve and explore the effectiveness of MS treatment, and leveraging machine learning methods could offer a promising solution. Although there may be potential benefits, the current research in this area is rather limited.

Methods: This study established three machine learning-based models to predict the unconfined compressive strength of MS that had been treated with sugarcane press mud (PM). The models included multivariate linear regression (LR), linear support vector machine (L-SVM), and quadratic support vector machine (Q-SVM). Percentages of PM content (i.e., 4%, 8%, 12%, and 16% by dry soil weight) and curing days (i.e., 7, 14, and 28 days) are used as independent variables (IVs) in model algorithms. The accuracy of the models was evaluated and validated using the R2, root mean square error (RMSE), and a series of residual analysis.

Results: The results demonstrated that all models were successfully trained and validated based on the experimental dataset. The Q-SVM algorithm showed superior performance in terms of both R2 (94%) and RMSE (4.4%), making it the best-fit statistical model compared to the LR and L-SVM models, which had R2 values of 79.2% and 75%, and RMSE values of 8.5% and 8.7%, respectively. In addition, insight from residual analysis revealed that Q-SVM model showed satisfactory trends of normal distribution, a symmetrical pattern, and a constant spread within the range.

Conclusions: Based on the results, the Q-SVM model appears to be more accurate and suitable for predicting the behavior of PM-treated MS. Therefore, the Q-SVM model is preferred and may be useful in practical applications. Overall, machine learning-based models may help reduce the time and cost of laboratory experiments without requiring extensive testing or large datasets. Future research may explore additional models such as Gaussian Process Regression (GPR) and Artificial Neural Networks (ANN) to further enhance the findings of this study.

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Keywords: mudstone soil; press mud; machine learning; unconfined compressive strength; soil treatment.

USING EXPLAINABLE ARTIFICIAL INTELLIGENCE TO UNDERSTAND LANDSLIDE SUSCEPTIBILITY

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Purpose: In recent years, the landslide community has primarily explored the use of Machine Learning (ML) models for mapping and predicting landslide hazards in terms of susceptibility and intensity. As for predicting landslide susceptibility, even though the ML methods have superior predictive performance compared to traditional statistical methods, they are primarily used as “black box” tools, without the possibility of understanding why the model is making decisions. This limits scientists’ understanding of the scientific consistency behind the model and decision makers whenever they need to plan risk mitigation actions. Thus, this research aims to improve on the explainability aspects of ML methods, by exploring why a particular model provides a certain probability score for a specific mapping unit.

Methods: To explain the results of a relatively simple neural network architecture, we used Shapely Additive Explanations (SHAP). Our model predicts the presence and absence of landslides in a particular slope unit as a pseudo-probability score. The model was trained and validated at the slope unit scale with a number of environmental independent variables such as slope, precipitation, lithology etc, as well as the ground shaking, due to the fact that the inventory we chose features coseismic landslides triggered by the Gorkha earthquake in Nepal (2015). After training and generalising the model, we calculated the SHAP values to measure the influence of individual variables on the predictive outcome of the model for the entire study area. This operation ensured a comprehensive overview of which factors are influencing the landslides in the region and how, even at the scale of a single mapping unit. Furthermore, to help the decision makers understand at individual slope unit level which factors affect the landslides, we created a Web Geographic Information System (Web-GIS) based platform, where decision-makers can click at the slope units and see which environmental variable is most responsible for potentially causing a landslide or not, at that specific location.

Results: Our research resulted in a new method to further expand the use of ML techniques in landslide hazard zonation with the application of explainable AI (XAI) and a Web-GIS platform for the decision makers (https://arcg.is/0unziD) to understand the role of factors behind landslide susceptibility. Furthermore, our research also provided insight into how these “black box” models make decisions about the geomorphological processes and how they prioritise the environmental variables. With this information and understanding of geomorphological processes, landslide scientists could better evaluate the performance of the ML models using scientific consistency rather than the evaluation metrics, often providing only half of the story.

Conclusions: XAI models provide better insights into landslide susceptibility predictions, when using any ML tool. We believe XAI plays an essential role overcoming the limitation of traditional “black box” ML models, both for landslide studies and in general for any geoscientific application where understanding the process is as crucial as the predictive capability of the model itself.

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COUPLING CORRECTED PRECIPITATION MODELS WITH LANDSCAPE CHARACTERISTICS TO FORECAST SHALLOW LANDSLIDES OCCURENCE IN PUERTO RICO WITH MACHINE LEARNING

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Purpose: Development of Machine learning (ML) models for landslide forecasting is complex due to the scarcity of a significant amount of recorded slope failure data available in the same extreme precipitation event. In addition, there is a paucity of real-time data of soil moisture measurements, the accuracy of the forecasted precipitation data, and reliable geospatial information on landscape characteristics. However, these data gaps have been filled for Puerto Rico after the passing of Hurricane Maria (H-Maria) in 2017. From the event, we now have an extensive landslide inventory of 70,000+ sites was generated (Figure 1; [1]) and can be coupled with high-resolution landscape information and real-time precipitation forecasting products.

Methods: This study describes the development of a ML model (Figure 2) that can be used to predict landslides with a resolution of 30-meters based on physical and dynamic variables before the occurrence of an extreme precipitation event in Puerto Rico. ML models were trained using the H-Maria event and included 18 explanatory variables, including landscape characteristics, weather, topography, and initial soil moisture variables; it is noteworthy that the corrected precipitation from a Weather Research and Forecasting (WRF) model was based on the Next Generation Weather Radar (NEXRAD) Level 3 precipitation dataset and the WRF model can forecast up to 48-hours ahead of time. The initial condition of the soil was incorporated by using the initial soil moisture and saturation from the GOES Puerto Rico Water and Energy Balance (GOES-PRWEB; [2]) model from the day before the prediction.

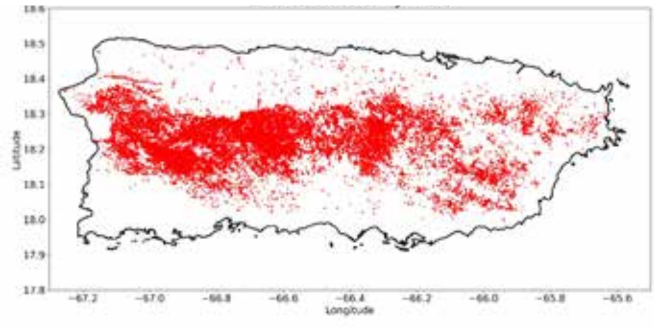

Fig. 1: Location of 70,000+ landslides triggered by H-Maria in Puerto Rico in 2017.

Fig. 2: Overall methodology.

Results: A grid of 30-meters was created over Puerto Rico in which each grid stores the dynamic and physical variables. In addition, each geolocated point of slope failures was overlaid with grids to find the number of failures per grid cell. As a result, two target maps were obtained; the first map stored either the occurrence of a landslide within a grid cell or not, and the second map stored either no occurrence, occurrence of one landslide, or occurrence of two or more landslides within a grid cell. Subsequently, the input data and each target variable were used to train different MLs to find the best model with the highest overall accuracy.

Conclusions: Preliminary results show that Random Forest ML got the best accuracy, followed by Gradient Boosting, with an accuracy of 85% and 82.5%, respectively, for predicting landslide hazard with two classes and 60.6% and 60.4% for predicting landslide hazard with three classes (See Table 1). We intend that the best-performing ML model be coupled to GOES-PRWEB and corrected WRF precipitation to generate landslide forecast maps in the days before an extreme precipitation event makes landfall.

Table 1: Accuracy results from the MLs

ML Algorithms	Accuracy using 2 classes (no LS, ≥1 LS)	Accuracy using 3 classes (no LS, 1LS, >1 LS)
Random forest	85.0%	60.5%
Logistic regression	78.5%	57.1%
Gaussian naive bayes	74.7%	55.2%
Nearest neighbor	81.7%	54.8%
Gradient boosting	82.5%	60.4%

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LAND-SUITE A SET OF TOOLS FOR STATISTICALLY-BASED LANDSLIDE SUSCEPTIBILITY ZONATION

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Purpose: A large variety of statistical models and methods have been proposed for landslide susceptibility mapping and zonation. The methods, applicable to a range of spatial scales, use a variety of input thematic data, different model combinations, and several approaches to evaluate the models' performances. Despite the numerous applications available in the literature, a standard approach for susceptibility modeling and zonation is still missing. In an attempt to provide a useful tool to cope with this limitation, the software LAND-SUITE was developed. The software provides a suite of tools for statistically based landslide susceptibility modeling and zonation.

Methods: LAND-SUITE is a suite of R tools released with an open-source license and aimed to support the landslide susceptibility inference process. It basically extends the LAND-SE software (Rossi and Reichenbach, 2016), which is mainly designed to perform statistically based susceptibility modeling. LAND-SUITE is composed of three modules, LAND-SIP (LANDslide Susceptibility Input Preparation); LAND-SVA (LANDslide Susceptibility Variable Analysis), and LAND-SE (LANDslide Susceptibility Evaluation).

Results: LAND-SUITE was developed to support the landslide susceptibility inference process, which is a complex task. LAND-SUITE facilitates and simplifies the testing of diversified geomorphological hypotheses, allowing the verification and discussion of the initial modeling assumptions, the preparation of less subjective statistically based susceptibility zonation, and the evaluation of the quality of the modeling results. The software was applied in different study areas, at different scales and to investigate diversified aspects of landslide susceptibility.

Conclusions: The suite demonstrated to have high flexibility allowing the use of different partitions of the training and validation dataset as well as diversified validation tests (e.g., temporal, spatial, crossvalidation), which are relevant evaluation steps to realize robust scientific susceptibility modeling exercises. LAND-SUITE can be used to model and evaluate the spatial probability of the occurrence of other types of natural phenomena (such as floods, forest fires, and rockfall source areas; see, e.g., Rossi et al., 2021).

SESSION 3.5

ROCK FALLS AND ROCK AVALANCHES (part II)

NUMERICAL MODELING OF ROCK AND ICE AVALANCHE AIR BLASTS ACCOUNTING FOR TURBULENT FLUCTUATIONS

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Purpose: Significant air blasts pressures are generated by rock and ice avalanches. The pressures are capable of uprooting trees, damaging buildings and causing human fatalities. The magnitude and spatial distribution of the pressure is difficult to predict because the cloud contains a mixture of particulate dust and air and shows significant turbulence. In this study, we propose a turbulent, depth-averaged model that accounts for both the laminar velocity and turbulent fluctuations to simulate the air blast dynamics of rock and ice avalanches.

Methods: The air blast model is established using depth-averaged equations, for mass conservation, momentum balance and additional equations associated with the production and decay of turbulent velocity fluctuations. The total turbulent energy of the air blast arises from three sources: the turbulent energy of the particulate dust as it escapes the dense flowing core of the avalanche, the shearing work in the cloud and finally the process of air-entrainment. The turbulent velocities of the air blast are directly calculated according from the turbulent energy, a non-directional, random quantity. We numerically solve the equations using well-established finite volume schemes within the RAMMS avalanche software. The model is applied to a recorded avalanche case study in Switzerland to show how turbulent energy within the air blast increases the hazard potential of rock and ice avalanches.

Results: Modeling results indicated that the turbulent energy leads to a higher instantaneous speed and pressure of the generated air blast, making it easier to damage the surrounding forests and infrastructure. The contribution of avalanche core, shearing work and air entrainment are influential, and the turbulent energy dissipates within a few seconds. Furthermore, we simulated a Swiss avalanche using the proposed model and assess the air blast power using the tree breakage information. High agreement between the modeling results and the field observations checks the validity of the proposed model.

Conclusions: Avalanche-induced air blasts are turbulent shear flows that rapidly propagate on mountain slopes. The turbulent energy is influential to the air blast dynamics and highly related to its power of destruction. The risk of air blast hazard might be underestimated if only accounted for the mean velocity. Our work proposed an approach to predict the air blast propagation and the impact pressure with contributions from both mean and turbulent velocity. This will improve the understanding on the air blast dynamics and aid in the related risk assessment in high-altitude mountainous regions.

MODELLING ROCK-SCREE INTERACTION IN A RIGID BODY AND HARD CONTACT FRAMEWORK

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Purpose: The accurate prediction of rockfall trajectories is of utmost importance for the planning of protection measures and creation of hazard indication maps. The most challenging part involves the modelling of the interaction between falling rocks with the terrain, which can have a wide range of properties ranging from soft meadows to hard bedrock. A rockfall simulation technique based on a non-smooth contact dynamics method with hard contact laws has proven to be a powerful tool in engineering practice. The combination with viscous drag forces and slippage dependent friction laws allows engineers to model the energy dissipation of rocks due to scarring in soft soils very accurately and efficiently. However, energy dissipation in scree interaction is fundamentally different. While a scarring-type model can produce satisfactory results for large boulders on fine scree, the differences increase as the rock size approaches the size of the deposited scree particles (e.g., small boulders on fine scree or large boulders on block fields). In the latter case, soil compaction disappears and energy dissipation is mainly controlled by surface roughness. Depending on the impact configuration, the rebound behaviour can differ drastically even on a very local scale. Boulders can roll across the terrain surface, lose contact with the terrain or experience severe impacts where all the energy is dissipated within one collision.

Methods: This work focuses on modelling this behaviour within the existing hard contact framework implemented in the RAMMS::Rockfall software. We incorporate the local roughness as a function of the size ratio between rock and scree using a stochastic approach. By randomising the normal and tangent vectors of the terrain at the impact location in the hard contact model, we can achieve the desired roughness effect. The new model is calibrated with data from real-scale field experiments with rock masses from 40 kg to 2.5 t.

Results: We validate the calibrated model with case studies and compare it to existing commercial rockfall simulation software. The calculated runout distances and jump heights of the rocks fit well with the observed events. Reducing the size ratio between rocks and scree increases the randomness of the interaction behaviour and thus also the mean energy dissipation. Furthermore, the comparison with existing software shows similar deposition patterns, but partly significant differences in the trajectories leading to deposition. This is mainly the case for small size ratios where roughness plays a role.

Conclusions: The new stochastic interaction model shows potential for an implementation in a trajectory modelling software for engineering practice. Since the roughness is mathematically accounted for within the contact mechanics instead of adding it to the digital elevation model (DEM), it is computationally more efficient as no high-resolution DEMs are needed. Although the same run-out distances and jump heights can be achieved with other calibrated interaction models, the new model has the advantage of an intuitive and measurable input parameter, namely the scree roughness.

TOPOGRAPHIC CONTROLS ON ROCKFALL RUNOUT DISTANCES WITHIN SANDSTONE CANYON TERRAIN IN ALULA, KINGDOM OF SAUDI ARABIA

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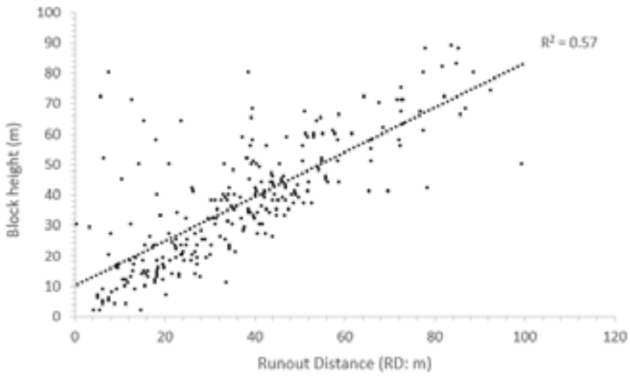
Purpose: Globally, rockfalls pose significant hazard to infrastructure and communities. It is therefore vital to have a quantitative understanding of to what distance from a rockfall source mitigation may be required to prevent occurrences of damage, injuries, or fatalities. Unfortunately, assessing potential rockfall runout distances (RD) is challenging, as numerous parameters control it (e.g. rockfall block characteristics, material properties of the impacted rock/soil such as coefficients of restitution (COR) and friction parameters, and the fall trajectory topography). Currently, there are few ways to rapidly assess potential RD to allow early communication of rockfall hazard to relevant stakeholders. Indeed, detailed field-based mapping and 2D modelling is typically required, and even then, the controls of different parameters remain unknown. Consequently, this work aims to isolate the effects of topography on RD, by undertaking runout modelling of 265 potential rockfalls in sandstone canyons in AlUla, Saudi Arabia, which have homogeneous geologies and material properties. By quantifying relationships between topography and RD, it is anticipated that topography based "simple rules" can be determined for estimating RD in this and geologically similar regions, to allow rapid communication of rockfall hazard to relevant stakeholders.

Methods: Fieldwork was undertaken to map the block characteristics, material properties, likely failure mechanisms, and slope geometries of 265 potential rockfalls in sandstone canyons in AlUla, Saudi Arabia. In addition, past runout distances were recorded. Using the obtained field data and a 0.5m resolution Digital Elevation Model (DEM), RocFall-2D software was used to model the 265 potential rockfall trajectories. Each model used 100 Monte-Carlo simulations that varied model parameters such as the COR around a normal distribution. Note that the COR values used were determined based on back analysis of the field obtained past runout data. The 95% percentile of the 100 simulated RDs was extracted for the 265 models. The RDs were then correlated with topographic indices (e.g. block height, mean slope angle) for each model trajectory.

Results: We find a linear relationship (R2 = 0.57) between total fall height and RD (Figure 1a). Additionally, RD is found to be normally distributed against the mean slope angle of the fall trajectory, with peak RD occurring at slope angles of 40 – 45o (Figure 1b). We also find a tentative threshold for the maximum RD that a slope of a given maximum angle can achieve.



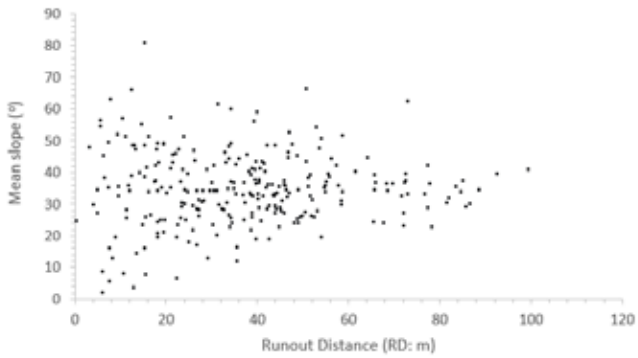


Fig. 1. Preliminary results showing a) (left) the correlation between rockfall block height and RD, and b) (right) the normal distribution of RD with mean slope angle.

Conclusions: These results provide evidence of how topography controls rockfall RD in AlUla. By combining the statistical relationships of slope angle, elevation, and RD, we expect to produce a "simple rules" matrix that will allows for rapid field-assessment of potential RD using observations of slope and elevation. This will enable rapid communication of rockfall hazard to designers and communities. Future work will refine and expand these relationships to assess how topography also influences rockfall characteristics such as total kinetic energy and bounce heights, and therefore also inform early rockfall mitigation design.

DEPENDENCE OF THE RUNOUT DISTANCE ON THE SHAPE AND ORIENTATION OF ROCKS

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Purpose: Rockfalls are a common geohazard in mountainous areas with a significant potential for damage to human lives and infrastructure. It is clear from experiment and observation that the shape of the rock has a large influence on the kinematics and runout behavior. However, numerical studies have been limited to either simplified geometries due to the complexity of appropriate force laws for non-round particles, or to only case studies in combination with complex slope topographies when more complex geometries were considered. In this work we systematically investigate the correlation between block shape and initial orientation and their effect on the overall behavior and runout dynamics of rockfall.

Methods: We use a two-dimensional "rigid-particle, soft-contact" method (a "penalty method" so that for sound propagation through space-filling packings of rectangular particles, the theoretical continuum sound velocity is reproduced) to model angular particles as convex polygons with different corner numbers and elongations. The particles are initialized with different initial orientation respective to their rotational symmetry before being dropped under gravity onto a simple inclined slope. The particle then moves (sliding, rolling or bouncing) until it comes to rest.

Results: When we vary the initial orientation, we observe that even slight variations in the initial orientation can lead to large variations in the final runout distance. Median runout for each shape increases with particle roundness but decreases with particle elongation. Further, particles with high corner numbers (i.e. more rounded) show a higher maximum runout distance, but with large scattering depending on their initial orientation due to incrementally accumulated differences at each bounce. More round particles also show consistently higher angular velocities upon impact on the flat ground compared to angular or elongated particles. The findings are consistent for different slope angles, initial drop heights and particle mass, and could also be observed in simple qualitative experiments.

Conclusions: In this study we have shown that rockfall is very sensitive to particle shape and initial orientation, which results in complex kinematics of the particle, a large variation in the particle trajectories and their runout distance. In contrast, round particles cannot predict the complex movement and kinematic quantities caused by the particles shape and tend to overestimate particle mobility.

TREE-INTEGRATION INTO FLEXIBLE ROCKFALL BARRIERS: FEASIBILITY, IMPLEMENTATION AND STRUCTURAL DESIGN

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There are typically two distinct strategies of protecting natural mountain hazards. A natural solution, when nature is supported by humankind, and a technical solution, when different interests restrict the natural solution, or it does not offer enough protection. The main keys to rockfall protection are protection forests and flexible rockfall barriers.

Until now, both have only been physically separated. This study, led by the approach of "nature-based solutions" (NBS), provides a strategy to permanently implement trees into rockfall barriers. It includes the tree physiological potential impact forces, the technical design, and the structural engineering dimensioning. The potential of trees is estimated through literature research. Further, the technical design is chosen out of already existing self-made tree-integrated systems and different ideas of fixation strategies. Moreover, the structural engineering dimensioning is done based on the European Guidelines of design steel and timber structures.

The literature shows that in cases of sudden dynamic impacts like rockfalls, there is stem breakage, but no uprooting observed. As a result, the potential impact force is solely determined by the wooden body, which is dimensioned in accordance with European guidelines. Related to the technical design shown in Figure 2, dimensioning would yield a minimum tree diameter at breast height (DBH) of 35 cm for a 500 kJ rockfall barrier. The study concludes that the designed TIS rockfall protection system would be feasible and structurally sound up to energies of 1000 kJ.

Summarised, the TIS rockfall protection system is an innovative solution that unites sustainable, low-CO_2 rockfall protection strategies with enhanced engineering components. It guarantees reliable, inexpensive rockfall protection, led by the approach of NBS.

THE INNONET PROJECT: UNDERSTANDING THE CAPACITY AND LIMITATIONS OF FLEXIBLE PROTECTION SYSTEMS AGAINST ROCKFALL IN NATURAL TERRAIN

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In the last 30 years, flexible rockfall barriers have become established worldwide as a protective solution. To ensure that these barriers can effectively stop the dynamic impact of rockfall, several guidelines have been introduced worldwide since 2001. They include proof of functional suitability through 1:1 field tests as well as proof of serviceability. In Europe, the approval and conformity verification procedures for rockfall protection nets, called ETAG 027, were introduced in 2008 and transformed into a European Assessment Document in 2018. This EAD specifies standardised and reproducible load cases.

The specification, however, of realistic service loads for flexible barriers is an ongoing concern in rockfall engineering. The question inevitably arises as to whether vertical drop tests, which do not consider block rotations, are representative of loads encountered by barriers in real terrain. The awareness that the capacity of a rockfall barrier is different depending on the impact location, and how to deal with the so-called remaining capacity of rockfall barriers, in load cases outside the approval tests, differ worldwide.

In 2019 an Innosuisse-sponsored 3-year research project was granted to the Swiss Federal Institute for Snow and Avalanche Research, together with the industry partner Geobrugg, for testing fully instrumented rockfall barriers. The experiments took place in the Swiss Alps, aiming at finding improvements to the capacity of rockfall barriers outside of the certification standards and defining substitute loads for the equivalent vertical drop tests at a testing facility. Several field campaigns were conducted, in which rocks of different shapes and sizes were projected into the netting of the rockfall barrier and its structure. The barrier was equipped with sensors to measure the loading on different elements of the protection system. In addition, the test blocks (up to 3'200 kg) were also equipped with sensors that measure the rotation and the acceleration during the fall and impact with the barrier. In combination with high-resolution drone recordings and video recordings from different viewing angles, the trajectories and velocities of the individual blocks were reconstructed in detail, enabling further insights into the interaction of all parameters.

Some of the results include that if disc-shaped bodies are to be expected and the topography allows an increase in their rotational speed, a reinforcement of the net for point loads arising from rock rotations should be considered. Indeed, falling bodies hitting a rockfall barrier with high rotational energies lead to higher loads than would be expected from testing and certification, according to the European Assessment Document (EAD). The length of the system needs to be adapted, as well as the lateral spreading, which is much higher with wheel-shaped blocks, and which results in a higher impact probability on border fields. The main danger is that the protective surface cannot absorb the increased forces and the higher tangential forces and fails. Two substitute loads that guarantee the best possible coverage along the entire length of the barrier line were, therefore, determined to reproduce the tangential forces caused by the rotation and consider border field hits.

AN ANALYTICAL MODEL FOR ROCKFALL BARRIERS ENERGY DISSIPATING DEVICES

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Purpose: Flexible barriers are worldwide commonly used in alpine and coastal environment as a measure to mitigate landslide hazard. These particular structures are regulated by an appropriate European Assessment Document (EAD) updated in 2018, in which their nominal life is supposed equal to 25 or 10 years, depending from environmental conditions. The previous assumption refers to all the technologies used for flexible barriers, neglecting variability of environmental conditions, installation and maintenance of these works. Among others, dissipating devices are key components for the structure response to impacts and represent the elements whose technology is the most variable from product to product. This work aims at providing analytical solutions to investigate the performances evolution of energy dissipating devices, according to different environmental conditions. Two commonly used technologies have been investigated. This work represents an initial attempt to accurately define a barrier service life.

Methods: The initial basic idea is to represent and analyze the flexible rockfall barrier as a complex set of components connected in series or in parallel. This would allow to examine the whole barrier through an analytical model that encompasses the wide variety of different technologies. In this pioneering phase, the research was mainly focused on energy dissipating devices, starting from an extensive literature review on scientific papers and mechanical engineering studies. Whenever information was lacking or controversial, tests were conducted in order to calibrate the model. Two device typologies among the most common in the market were studied, modifying materials properties considering, among other possible damages, environmental corrosion.

Results: In this study, the behaviour of the single components demonstrated remarkable sensitivity to corrosion variations. This suggests that a noticeable influence should also be present on the whole structure and gives confirmation to the need of further research. For the energy dissipating devices, i.e. brakes, the differences between experimental and analytical results are acceptable both in static and dynamic conditions, confirming the model potential.

Conclusions: Starting from dissipating devices, this work represents the first step towards the creation of an analytical model for the whole barrier, which can contribute to the inspection and assessment of barrier and to predispose effective maintenance programs.

FAILURE VALUES OF ROCKFALL EARTH PROTECTION EMBANKMENTS: A PROPOSAL FOR THE ULTIME LIMIT STATE DESIGN

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Purpose: Reinforced earth rockfall protection embankments (RPE) represent a widely adopted protective measure against rockfalls especially in case of repeated events or with extremely high kinetic energies. At present, a unique design method used for this type of work has not been codified yet. Energy-based approaches are frequently adopted, where the design consists in assessing that the structure deformation required to dissipate the block's kinetic energy is consistent with embankment dimensions. Nevertheless, the analytical correlations, which allow to determine the displacements involved in the impact on both the sides, have not been extensively calibrated for RPE. In addition, maximum allowable displacements to prevent failure are often defined considering the equilibrium of the non-impacted layers as rigid bodies or, for the downstream side, a percentage of the wrap up length of the reinforcing material. This work aims at defining the limit deformations of the embankments through both experimental and numerical investigations, that can thus be adopted in the design procedure.

Methods: In this paper reduced-scale tests have been performed. To preliminary investigate the dissipation by friction, quasi-static lateral punching tests have been conducted to effectively evaluate the volume of the RPE involved in the sliding process. The results have been scaled to real geometries, according to principles of similitude and π-theorem. The results have been used to calibrate a FEM numerical model and to perform a huge variety of simulations to investigate the effects of geometry and the properties of both the RPE and the impacting block.

Results: The results of experimental and numerical simulations allow to determine the limit deformations. Useful relationships to correlate the limit downstream deformation and the ratio between the reinforcement wrapped length and the size of the layers involved in the impact are provided.

Conclusions: The obtained results provide useful insights for the design phase and the assessment of existing RPE.

SESSION 4.3

WEAK POINTS IN LANDSLIDE SUSCEPTIBILITY MODELLING (part I)

INFLUENCE OF THE LANDSLIDE INVENTORY COMPLETENESS ON THE ACCURACY OF THE LANDSLIDE SUSCEPTIBILITY MODELLING: A CASE STUDY FROM THE CITY OF ZAGREB (CROATIA)

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Purpose: The quality of landslide susceptibility maps depends on the quality of the input data, i.e. the spatial resolution and accuracy of the landslide conditioning factor maps and the completeness and accuracy of the landslide inventory map. For the pilot area (21 km^2) in the City of Zagreb (NW Croatia), a detailed landslide mapping was done based on visual interpretation of high-resolution LiDAR DTM. The result was the LiDAR-based inventory with 702 landslides (min = 43 m^2, max = 8,064 m^2, median = 400 m^2). The purpose of this study is to test the relevance of landslide inventory completeness and its influence on the landslide susceptibility model (LSM). By analysing different ratios of landslides for model training and validation, we aim to provide new insight into the need for detailed landslide mapping for large-scale susceptibility modelling, as well as the impact on the final landslide susceptibility map.

Methods: Landslide susceptibility modelling was performed based on 5m pixel-based analysis, Random Forests machine learning method and ten landslide conditioning factors. The landslide susceptibility analysis consists of nine scenarios (S1 – S9) that were defined considering the percentage of landslide polygons in the inventory for model training (S1 = 90%, S2 = 80 %, S3 = 70%, etc.), while the rest of the landslides were used for model validation (S1 = 10%, S2 = 20 %, S3 = 30%, etc.). The performance of landslide susceptibility model training and validation was measured with the Area Under the ROC Curve (AUC) metric.

Results: The results are part of the scientific research project “Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology” (LandSlidePlan, HRZZ IP-2019-04-9900). Presented analyses showed that using 90% of inventory landslides for model training and the rest 10% of landslides for model validation (S1) resulted in LSM with a training AUC value of 98.1% and validation AUC of 93.0%. Using landslide inventory, split into two equal datasets (S5), one for training and the other for validation, keeps the training AUC value higher than 98 %, and validation AUC slightly decreased to 88.4%. Furthermore, LSM trained with only 10% of inventory landslides (S9) resulted in training AUC value higher than 99 %, whereas validation AUC dropped to 85.1%.

Conclusion: Based on the conducted landslide susceptibility analysis, using a significantly small percentage of landslides for model training can result in LSM with high validation AUC (> 85%). Moreover, in the presented study, detailed and completed geomorphological LiDAR-based inventory, LiDAR DTM morphometric derivatives, small-scale geological data, and high-resolution land use data proved to be enough to derive an LSM with validation AUC values higher than 85 %. It can be concluded that for relatively smaller homogeneous areas, regarding geomorphological and geological conditions, it is possible to carry out a large-scale landslide susceptibility assessment with a relatively small number of mapped landslides if they are a representative sample of landslides in the study area or uniformly distributed throughout the study area.

IS ANY INVENTORY VALID FOR SUSCEPTIBILITY? EXPLORING AVAILABLE LANDSLIDE INVENTORIES IN GIPUZKOA PROVINCE (SPAIN)

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Purpose: As in many landslide-prone areas of the world, in Gipuzkoa province (northern Spain), landslides are recurrent and commonly cause damage to communications infrastructure such as roads and railways. This geomorphological process also threatens buildings and human beings, although in a lesser level. Despite the individual effort dedicated by different institutions, as well as academic research groups, basic and crucial information about historic and ancient landslides occurred in this territory – i.e., landslide inventories – is incomplete or unevenly distributed along the province. Landslide inventories play a relevant role, since they are actually the base line to calibrate numerical models or innovative automatic landslide mapping approaches. In most cases, the information contained in a landslide inventory is taken at face value, probably due to the scarcity of data providing the location of past landslides. However, landslide databases often show systematic bias related to the spatio-temporal scale, the considered data sources or the representation criteria, which conditions their completeness and representativeness. This is definitively a weak point of many landslide susceptibility projects. The aim of this communication is to present the state of the art on landslide information through the description of the existing landslide inventories that have been carried out in Gipuzkoa until the date.

Methods: Among the collected information, five landslide inventories were in digital format and 11 on paper maps, spanning the period 1991 to 2018. Concretely the five digital databases were exploited and compared in this work, in order to assess their differences as well as to investigate the relevance and the implications of the inventories related to their derivative products, such as susceptibility models. For instance, we calibrated 5 landslide susceptibility models and highlighted evident differences in the results depending on the used landslide inventory for calibration.

Results: The addressed work allowed highlighting the exceptional efforts made by different institutions and private individuals to compile sixteen landslide inventories with different purposes within the Gipuzkoa province. The statistical analysis of five digitized landslide inventories, four of them sometime used to generate susceptibility maps, has revealed remarkable differences between them. Such differences are mainly related to the characteristics of the single/multiple data sources used to obtain the information and to the objectives of each database, which condition such issues as the size of the study area, the covered temporal gap and the type of landslides under study, among others.

Conclusions: Among the analysed inventories, we conclude that two (GeoEuskadi and Bornaetxea News) are not adequate to asses landslide susceptibility by means of data-driven methods. The other three inventories (INGEMISA, Lower Deba and Bornaetxea Field) have presented enough guarantees to perform such analysis, although the combined usage of all these three data bases offered a more plausible and generalizable result, according to the Area Under the ROC Curve (AUC), the Empirical Cumulative Density Function (ECDF) test and also the authors' judgement.

DATA-DRIVEN LANDSLIDE SUSCEPTIBILITY ASSESSMENT: CHALLENGES, FLAWS, AND WORKAROUNDS - EXAMPLES FROM THE PROJECT "MASS MOVEMENTS IN GERMANY"

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Purpose: Numerous scientific research endeavors are devoted to assessing landslide susceptibility using data-driven methods. While many studies have focused on the model-centric approach, which involves comparing different models on a specific dataset and selecting the best-performing one, the generated landslide susceptibility maps' reliability depends strongly on the quality of input data. Unfortunately, detailed data uncertainty assessment has not received adequate attention in the past. This paper addresses the challenges associated with the data commonly used to conduct landslide susceptibility assessment (LSA). By drawing examples from the project "Mass Movements in Germany", we explore the limitations and potential biases of the data used in LSA and propose strategies to mitigate these issues. Ultimately, we hope to contribute to developing more reliable and accurate landslide susceptibility maps.

Methods: We focused on the statistical Weight of Evidence (WoE) method, which is straightforward and provides well-interpretable results. Through different consecutive experiments, we scrutinized the effects caused by independent variables derived from thematic layers at different scales available in Germany. In collaboration with local experts, we evaluated the reliability of the maps based on their local knowledge. In case of significant discrepancies between model outcomes and expert opinion, we re-designed the input data to better characterize the local conditions supported by concepts of causal reasoning.

Results: Our experiments revealed that scale-based data flaws are inevitable when using thematic layers to derive covariates for LSA beyond their initial purpose. We encountered generalization effects in all information layers depicting geological conditions. Also, the quality of the landslide inventory dataset significantly impacts the final susceptibility patterns. Moreover, it is challenging to identify biases in input data on the model side as the evaluation metrics, such as the area under the receiver operating characteristics curve (AUROC), may provide comparable values for differing (also not reliable) susceptibility patterns. The applied data-centric approach enhanced the reliability of models but has limitations and does not generalize to other regions if the applied data design is too specific.

Conclusions: The concept "Garbage In, Garbage Out" is universal in all parts of reasoning based on data or knowledge. Thus, acquiring accurate datasets is a significant effort in all branches of data-driven applications, as uncertain or incomplete data can lead to incorrect or unreliable conclusions. Therefore, a data-centric approach that prioritizes data quality and integrity is more important for the model's reliability than a decision about which classification algorithm to use. Finally, it is essential to acknowledge the limitations and potential biases of input data and develop strategies to mitigate these issues for developing more reliable and accurate landslide susceptibility maps.

ASSESSMENT OF BENCHMARK DATASETS FOR LANDSLIDE SUSCEPTIBILTY ZONATION

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Purpose: Landslide susceptibility is the subject of countless scientific publications [1-8]. Different authors use heterogeneous data, and apply many different methods, mostly falling under the definition of statistical and/or machine learning with the common feature of considering many input variables and a single target output, denoting landslide presence. Obtaining landslide susceptibility is a classification problem: given N input variables assuming different values, each combination associated with a 0/1 possible outcome, a model should be trained on some dataset, validated with unseen data, and eventually applied to (tested with) unlabeled data for prediction. Input data (predictors, factors, or independent variables) are a mixed set of topographic, morphometric, environmental, and climatic data; a landslide inventory plays the role of dependent variable. Choice of a specific classification method depends on software availability, personal background, and existence of relevant literature in the area of interest. New methods appear regularly in the literature, and it is often difficult to judge their performance with respect to existing methods [9]. We aim at establishing a common baseline for a transparent comparison of the plethora of existing methods [10].

Methods: A meaningful comparison of many different methods would require a common dataset – namely, a benchmark - to train and validate each of them in a systematic way. This is a standard procedure in machine learning science and practice, for virtually all the fields: benchmark datasets exist for medical sciences, image recognition, linguistics, and in general any classification algorithm. In the case of landslide susceptibility, we believe that maps should be devised based on slope units [11-13], as they have a meaningful correspondence with topography, at variance with square grid cells. Thus, we decided to adopt a subset of the slope unit dataset used by [14] in Italy.

Results: We report about a collaborative effort recently proposed by the authors of this contribution. We selected a benchmark dataset and disclosed it to the landslide research community, asking researchers to apply their favorite classification method to obtain landslide susceptibility maps for the area. Results about performance of individual tested methods will be collected (session at the EGU 2023), and will be discussed during this presentation. Both dataset and results will be available to the landslide research community.

Conclusions: The outcome of this effort represents a meaningful comparison of the performance of different classification methods, and it provides a solid reference for the development of new methods. We argue that additional benchmark datasets are desirable, in order to represent different geographic, geomorphological, physiographic and climatic conditions and to assess the performance of classification methods in different areas.

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COMPILATION OF INVENTORY AND CHARACTERIZATION OF LANDSLIDES FOR LANDSLIDE SUSCEPTIBILITY MODELLING IN WESTERN CANADA

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Purpose: As a 1st step in assessing landslide susceptibility modelling, compilation of a landslide inventory is essential. The 2nd step is to create a susceptibility model that will highlight areas prone to landslide occurrence. The resulting landslide inventory and susceptibility maps then serve as baseline information to help stakeholders, decision-makers, and practitioners further assess hazard and risk. As part of Natural Resources Canada, the Geological Survey of Canada's Public Safety Geoscience Program has carried out landslide inventory and susceptibility mapping in western Canada in collaboration with provincial, territorial, academic partners, and consultants. The regions highlighted in this presentation are the Sea to Sky corridor, Douglas Channel, east of Kitimat and Sutherland landslide near Fort Fraser (BC), and the Alaska Highway, Yukon.

Methods: The simplest landslide susceptibility modelling approach for a large area is the qualitative heuristic method. This approach was first tested along the Sea to Sky corridor in southwestern BC for debris flows and rockfalls/rock slides. For the Yukon Alaska Highway corridor, qualitative heuristic assessments were tested for active layer detachment slides (ALD) and debris flows. Near Kluane Lake, a quantitative debris flow susceptibility model using Flow-R was tested. A landslide inventory of Douglas Channel in north coastal BC revealed folic debris slides as the most abundant landslide type (>1000). Hence the BC terrain stability method was used. The Sutherland landslide, in north central BC, occurs in moderate relief terrain with volcanic basalt overlying weak volcaniclastics rich in swelling clays. Modelling proved difficult due to the characteristics of this complex landslide.

Results: Along the Sea to Sky corridor, the historic record of debris flows, and rockfalls/rock slides proved to be essential for the inventory, characterization, and validation of susceptibility models because debris flows recur in the same steep channels, and rockfall boulders are quickly removed. Thus, evidence quickly disappears. For the Yukon Alaska Highway, validation of the ALD susceptibility model proved to be difficult because ALD are small, localized, and have a short lifespan (~25 years). In the Kluane Lake area, susceptibility modelling proved successful because the debris flow inventory was well documented, and data derived from a high-resolution DEM were available. For Douglas Channel, susceptibility modelling was challenging since folic debris slides are abundant, small, and triggered during rainy periods. Furthermore, their impact on infrastructure, public safety, and natural environment is considered minimal. Sutherland landslide was also challenging for susceptibility modelling because failure of underlying volcaniclastics contributes to failure of overlying basalt cap rock. Moreover, the rigid overlying unit and low slope gradient are not usually indicative of large slope failures. Two characteristics commonly used as parameters to model landslide susceptibility.

Conclusions: Each region possesses unique landslides affecting the landscape of western Canada. In the Sutherland landslide case, the volcanic and volcaniclastic assemblage should be used as one unit in a model with the assumption that volcaniclastics are present underneath the basalts. Understanding the characteristics of landslides help determine the data layers required in the susceptibility models, and evaluate whether modelling is warranted for certain areas.

THE ACCURACY OF THE SUSCEPTIBILITY MAPPING IN MAN-DEVELOPED AREAS

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Purpose: Many aspects affect the accuracy of susceptibility mapping: the use of different statistical methods, the scale of the study, the use of independent factors, the accuracy of causal factor maps, the accuracy of landslide inventory and data availability. This study focused on the problems with accuracy that have not been widely discussed in scientific literature so far, i.e. homogeneity of a study area and causal factors undetectable by statistical methods.

Methods: The cross-disciplinary studies were brought together to address the problem of accuracy. This study investigates landslide susceptibility assessment using geographic information system (GIS)-based statistical models in different areas – urban areas and river valleys. The following methods were used: the frequency ratio and predictor rate method (FR & PR), the weight of evidence (WOE) and logistic regression (LR). The performance of the susceptibility model was evaluated using the success and prediction rate criteria. For validation of the accuracy of the susceptibility maps the fallowing were used: field surveys, analysis of archival materials, numerical modeling and airborne laser scanning (ALS) data analysis. Three different areas in Northern Poland were considered, mainly: the Tri-City, the Lower Vistula and the Central Radunia valleys.

Results: Homogeneity of a study area is important. For the Lower Vistula Valley landslide susceptibility assessment by the FR & PR method a homogeneous physical-geographical region was selected. Such homogeneity of an area makes it possible to limit the analysis only to landslides formed under analogous geoenvironmental conditions. The very good results of susceptibility verification maps for various combinations of causal factors indicate the importance of geomorphological and geological homogeneity. Not all relationships between the conditioning factors and landslides observed during field work can be modeled through statistical methods. Limitations arise because of the dynamic, changeable, and expansive character of the processes that occur in man-developed areas. Causal factors that are undetectable by statistical methods become apparent through field surveys, analysis of archival materials and numerical modeling. A separate issue is the sensitivity of statistical method to the cross-correlation between causal factors. Many studies confirm that the use of an independent dataset in modeling and validation is fundamental. In the susceptibility assessment of the Vistula Valley, correlated topographic attributes were used. This did not have a major impact on the susceptibility analysis because of the small difference between the models containing strongly and very strongly correlated data and the other models containing uncorrelated or moderately correlated data. For the frequency ratio method, the correlation between data does not significantly inhibit the ability to obtain a good fit and does not affect the inference.

Conclusions: The results show that the homogeneity of the study area, accuracy of causal factor maps and the ability to present causal factors by maps are the aspects that effect the accuracy of the susceptibility maps.

CELL SIZE INFLUENCES THROUGH DIFFERENT LANDSLIDE TYPOLOGIES IN LANDSLIDE SUSCEPTIBILITY MODELLING

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Purpose: In this research, a systematic inventory for the three different types of landslides (rotational/translational slides, slope-flows and local flows) was exploited for investigating the effect of the cell size on the inner structure (i.e., the involved controlling factors) of the three derived susceptibility models and on their predictive performance (accuracy and reliability). In fact, using the same source data and different slope failure types offered a key to the interpretation of any predictive performance changes produced by cell sizing (5, 8, 10, 16 and 32 m), also considering the geomorphological suitability and adequacy of the related factor selection.

Methods: Ten variables were exploited as potential predictors: elevation, steepness, aspects, expressed here in terms of northerness and easterness, topographic curvatures expressed in terms of plan and profile curvature, topographic wetness index, the stream power index, landform classification, outcropping lithology and soil use. The Multivariate Adaptive Regression Splines (MARS) method was employed to detect the relations between the outcome and predictors. For each model, the prediction skill in evaluating the blinded 25% (prediction) and 100% (success) of the archive was analyzed by exploiting all of the validation indices/tools (ROC-plot, AUC value and confusion matrix). On the other hand, an in-depth comparison of the employed geo-environmental variables (or classes) for the construction of the fifteen models was carried out.

Results: The results confirmed the expected influence of the mapping units' size on the accuracy of the models. However, the higher-resolution model (5 m) did not produce the best performance for any of the landslide typologies. The model with 8 m-sized pixels displayed the optimal threshold size for slides and slope-flows. In contrast, for local-flows, an increasing trend of model prediction accuracy was reached with 32 m pixels. The variable importance analysis demonstrated that the better performance of the 8 m cells was due to their effectiveness in capturing morphological conditions which favour slope instability (profile curvature and middle and high ridges). Lithoid units' class was the only outcropping lithology selected for slides, whilst clays and marly clays were also selected for slope-flows. At the same time, local-flows selected a large fan of outcropping lithologies. Elevation and slope steepness play a strong controlling role in general slope instability conditions and were selected as ubiquitarian factors. Slides and slope-flows were shown to be more sensitive to slope geometry and to topographic wetness index (proxy of the role of potential water saturation in the failure mechanism).

Conclusions: The optimal selection of the cell size has to be based on multiple modelling so as to analyse and explain differences and more objectively select the best size. The small but significant differences in the AUC performances corresponded to weak but coherent differences in terms of binarized predicted status. In this sense, when using grid cells as mapping units, it is essential to verify the robustness of a model to the change in cell size for the evaluation of either the reliability and the geomorphological adequacy of the obtained results.

INFLUENCE OF LANDSLIDE CONDITIONING FACTOR SELECTION ON LANDSLIDE SUSCEPTIBILITY MODELLING IN LARGE SCALE

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Purpose: In Hrvatsko Zagorje region, NW Croatia, a significant amount of landslides threatens the elements at risk. To address the issue, LiDAR data from airborne laser scanning was obtained in the frame of the scientific research project "Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology" (LandSlidePlan, HRZZ IP-2019-04-9900), funded by the Croatian Science Foundation. The LiDAR digital terrain model was used to create a complete landslide inventory and derive most of the landslide conditioning factors (LCFs). The purpose of this study is to test LCFs individual relevance and influence on large scale landslide susceptibility models (LSMs), including the number of used LCFs and their combination. Finally, by testing and optimizing the scenarios we aim to provide new insight into landslide occurrences in the study area, as well as optimize the LSMs.

Methods: In a pixel-based analyses, 15 LCFs were used in Random Forests machine learning method to derive landslide susceptibility maps. Landslide inventory was split into two equal datasets considering the amount of landslide polygone presence, one for training and the other for validation. Both training and validation performance was measured with Area Under the ROC Curve (AUC) metric. The calculated AUC values were observed to determine the LCF importance and influence on the LSMs in the defined scenarios.

Results: Analyses showed that using only five properly selected LCFs is enough to derive LSMs having >96.0 training and >76.0 validation AUC values. On the other hand, highest AUC validation values at >80.0 are possible by using 10 or more LCFs. Adding or removing single LCFs is neglectable when using a larger amount of LCFs, an exception being curvature and terrain dissection LCFs which are identified as the two most significant. Furthermore, minimal usage of two or three LCFs still keeps training AUC values higher than 90.0, whereas validation performance drops to 71.2 or lower. Absence of lithological units or proximity to geological contact LCFs leads to a slight increase in AUC validation.

Conclusion: The combination of LCFs and the presence or absence of certain LCFs is less influential when a larger number of LCFs are used. On the contrary, using significantly fewer LCFs can be sufficient if a proper combination is selected, considering that the input data is of proper scale. In addition, a poor combination of a low number of LCFs can drastically decrease AUC validation values. Determining LCF influence is crucial in optimizing LSMs and can lead to deriving sufficient landslide susceptibility maps without having a variety of LCFs at disposal. Particularly, in this study LiDAR derivatives and anthropogenic LCFs proved enough to derive a LSM with training AUC values of 98.7 and 80.7 for training and validation, respectively. The latter AUC values are insignificantly lower compared to the highest possible we managed to achieve by optimizing the combinations.

UPDATED LANDSLIDE SUSCEPTIBILITY ZONE MAP OF THE UNITED STATES

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Purpose: Landslide susceptibility maps are fundamental tools for spatially characterizing the potential for landslide occurrence. These maps can inform emergency management, resource conservation, land-use planning, and infrastructure development. National-scale, landslide-susceptibility maps are important for objectively identifying hot spots and for prioritizing site-specific studies; the variability in landslide types, triggering conditions, and resolutions of available data also pose a challenge. In contrast, prototype maps of landslide non-susceptibility zones based on simple slope-relief thresholds were developed for the conterminous United States (U.S.) in 2012, the Mediterranean region in 2015, and most of the world in 2021. Each of these efforts used 90-m-resolution topography and collectively, these cover 80% of the Earth from 56°S to 60°N. Although these maps provide some insight on areas where landslides are unlikely, their use for emergency management and other societal planning is limited due to the coarse resolution of the input topographic data and the resulting 1-km-resolution grid cells. Other existing national-scale U.S. landslide susceptibility maps are also of limited utility because the underlying models rely on the same coarse topography and underrepresent landslide potential in moderate-to-low susceptibility terrain. This poor performance is demonstrated based on a comparison with about half-a-million bedrock and shallow landslides and related deposits or features that have been mapped across the country. Given the societal value for understanding landslide potential, further work is warranted to enhance national landslide-susceptibility mapping.

Methods: We present an updated effort to map national-scale susceptibility zones for all types of landslides in the U.S. using the same slope-relief threshold approach used in previous efforts, but with several notable advances. First, our analysis is based on finer-resolution (10 meter), nation-wide topographic data, resulting in a higher-resolution map (90 meter instead of 1 km). Second, our analysis extends beyond the conterminous U.S. (CONUS) footprint of the prior approaches to include all of Alaska, Hawaii, and Puerto Rico. Third, we incorporate a substantially larger inventory compilation (> 612 thousand landslides) than any previously published susceptibility assessment. Fourth, we consider geographic influences and variability in landslide occurrence across the country using defined ecoregions to constrain the threshold. Fifth, we implement an objective split-sample calibration of the slope-relief threshold.

Results: We use simplified metrics to assess the balance between the percentage of landslides correctly classified by the threshold and percentage of land-surface area covered by potentially susceptible area. A more traditional performance evaluation would be misleading, given that the U.S. landslide inventory compilation is known to be incomplete over large areas of the country. The original USGS map captures 79% of those landslides within CONUS and covers 31% of the land surface area, the CONUS part of the global map captures 62% of those landslides and covers 19% of the area, and our map captures 97% of landslides, covering 33% of the area.

Conclusions: Our improved map is more accurate and has finer resolution than previous products. It could be used to determine where landslides may not be a major concern and where more-detailed, site-specific investigation of landslide hazards could be warranted.

IS SUSCEPTIBILITY JUST A SPATIAL ASSESSMENT? A THEORETICAL MODELING ENDEAVOR ON THE IMPORTANCE OF TEMPORAL DATA RECONSTRUCTION!

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Purpose: Landslides can occur in different periods under different predisposing factors that are changed over time or no longer exist. We aim to address how discarding this important rule or assuming conditions to be intact can be detrimental in fast-evolving regions as it can easily mislead susceptibility models. Instead, this research prompts researchers to produce "multi-temporal thematic maps" and historical reconstruction of the main causative conditions in the past.

Methods: To build our case from scratch, we used a popular landscape creation tool for game engines tool called TerreSculpture and its versatile feature, "Rainfall Erosion", to build our own artificial digital elevation models (ADEMs) with an arbitrary 20-year interval: 1960, 1980, 2000, and 2020. The DEMs of Difference (DoD) method was used to create erosion/deposition sites by which we were able to produce three landslide datasets (Figure 1). Further, DEM-derived morphometric indices were extracted for each year in SAGA-GIS to be used in the susceptibility modeling (Figure 2). We also tried to consider the drastic land use/cover change of Northern Iran we deliberately selected two contradictory phases of land use/cover changes: 1) destructive phase, and 2) recent constructive and compensation activities (Figure 3). The latter made two susceptibility scenarios that were modeled using Maximum Entropy (MaxEnt) model: 1) the strategized modeling that considers the aggregation of historical information of landslide events, and 2) the blind modeling where all the historical changes and developments are neglected, and only the current condition is used for modeling.

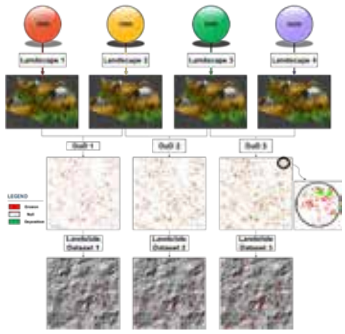

Fig. 1: The procedure of creating historical ADEMs, DoDs, and landslide events in TerreSculptor and ArcGIS.

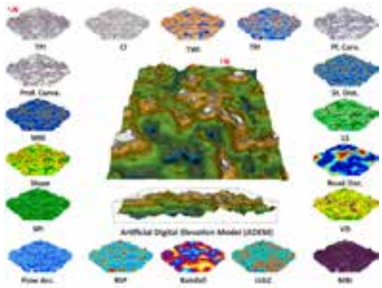

Fig. 2: DEM-derivative morphometric indices produced for four ADEMs in four stages in time.

Fig. 3: The land use/cove change narrative adopted in this research.

Results: The graphical results revealed that blind modeling is exposed to two main error types: type I (false positives) and type II (false negatives) (Figure 4). Moreover, the response curves derived from the two scenarios can be entirely contradictory (Figure 5). The blind model was unable to extract the correct responsive curve of morphometric indices and the main land use classes that primarily predisposed the area to historical landslide occurrences.

Conclusions: Given that landslides can occur in different periods, landslide susceptibility, in the first place, cannot be modeled merely by their spatial attribute, but they are entangled with time. The results of this research can be attributed to the inconsistent results that may be offered by any landslide susceptibility mapping effort that defies the changes in landscapes and, thus, the underlying cause-and-effect relationships.

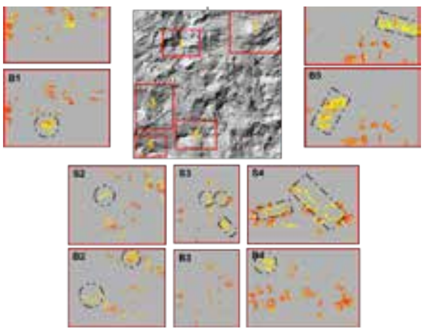

Fig. 4: Graphical comparison of strategized and blind landslide susceptibility modeling results.

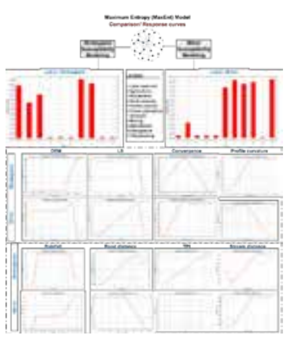

Fig. 5: Comparing the response curves between strategized and bind landslide susceptibility models.

SESSION 5.2

LANDSLIDES IN THE COLD REGIONS AND EXTREMES (part I)

STABILITY OF FRESHLY DEGLACIATED MORAINE IN THE HIGH ARCTIC - HORNSUND FJORD, SVALBARD

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Purpose: Slope movements in the High Arctic are not yet a satisfactorily studied topic. As the Arctic is one of the fastest-warming regions in the world, an increase in landslides can be expected. The Hornsund Fjord area in southern Spitsbergen is a geologically and geomorphologically very diverse area, including rocks from Proterozoic to Tertiary and Holocene moraines. A wide range of slope processes occur in this environment, from large rock avalanches to small landslides and flows in the moraines. This paper focuses on the most recent process - landslides in the freshly deglaciated moraine of the Hansbreen Glacier.

Methods: Repeated UAV mapping, digital terrain model analysis and laboratory analysis of soil samples were used for the research, along with a simple stability model.

Results: The results show the occurrence of two types of landslides. Primary, involving unsorted moraine material, occur at the top of the slope, while secondary, occur in the already outwashed fine material below. The results also show that moraine stability is primarily controlled by the amount of meltwater available. The landslides can therefore be considered as flows rather than landslides sensu stricto. The stabilisation of active landslides after deglaciation occurs relatively early, almost immediately after the water pressure dissipates. Their further reactivation is then conditioned by the recharge of the slope by additional meltwater or intense precipitation.

Conclusions: The results of this research have important implications, as these freshly deglaciated, unstable areas will extend significantly in the next years following the glacier retreat. However, their immediate stabilization will in principle be very rapid if no further water input occurs. If more meltwater or rainfall occurs, localised destabilisation of already stable areas may occur.

PERMAFROST CONTROLS LONG-TERM DISPLACEMENT ACTIVITY OF LARGE UNSTABLE ROCK SLOPES IN ARCTIC AND SUBARCTIC NORWAY

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Understanding the impact of climatic changes and connected variations in permafrost occurrence on large unstable rock slopes is crucial for successful risk assessments and management strategies in arctic and subarctic environments. A potential catastrophic failure of such a large rock mass in a populated area can have severe consequences for the local society. Norway has a 6-6.5% permafrost cover today and continues to experience spatial and temporal variations in permafrost. It is therefore fundamental to determine the sensitivity of large unstable rock slopes to changes in ground temperatures.

We have reconstructed the timing of displacement initiation and potential late Pleistocene and Holocene sliding rates for six active gradually deforming rockslides in Norway. For this, we have established exposure duration chronologies along vertical transects over the outcropping parts of the sliding planes. In a second step, we have evaluated the timing of initial displacement and pre-historical slip-rates considering a possible climate control by modelling the permafrost evolution since deglaciation for three unstable rock slopes: Mannen, Revdalsfjellet and Gamanjunni 3. Deformation at these sites started during or at the end of the Holocene Thermal Maximum (HTM), between 8 and 4.5 ka when permafrost in those regions was mostly degraded. At two low elevation sites, Oppstadhornet and Skjeringahaugane in western Norway, where permafrost remained absent during the Holocene, deformation initiated shortly after deglaciation.

The timings suggest that the presence of permafrost in Norwegian rock slopes had a stabilizing effect over several millennia after deglaciation. After initial deformation sliding rates seem to have decreased throughout the Holocene at all analysed rock-slope instabilities. However, modern measured sliding rates at four sites indicate a moderate to strong acceleration, compared to previous displacement rates. Three of these sites are located above or at the lower limit of alpine permafrost, where recent permafrost degradation may enhance displacement activity. The implication is that on one hand slope failures in Norway may become more frequent during accelerated warming, while on the other hand, unstable rock slopes may stabilise after complete permafrost degradation.

KINEMATIC EVOLUTION OF A PARAGLACIAL LANDSLIDE EMPHASIZES THE NEED FOR REGULAR HAZARD RE-EVALUATION

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Purpose: The response of individual slopes to glaciation and deglaciation is spatially and temporarily variable and many geologic, topographic, and paraglacial factors is required to identify expected changes as well as potential resultant hazards. Few studies exist that surveil and track the impact of active glacier downwasting and retreat on the stability of fjord walls. In the Barry Arm fjord of Alaska, repeat, high-resolution aerial and satellite data provide a unique opportunity to learn how a large bedrock landslide with a receding and thinning glacier at the toe is deforming. If the landslide were to fail into the fjord, it has the potential to generate a tsunami that could adversely impact activities in and around the region.

Methods: We utilize structural and kinematic mapping, aerial lidar, satellite and ground-based radar interferometry, and seismic monitoring to quantify deformation of the Barry Arm landslide. Mapped structures and kinematic elements reflect the cumulative, differential patterns and amounts of movement since the inception of a landslide. In contrast, lidar differencing and InSAR capture current and ongoing movement patterns. Seismic data provide precise event timing of rockfall events that may be related to widespread landslide movement, which helps to further reveal details of landslide behavior. Used together, these methods help to define how the Barry Arm landslide has moved in the past, how the landslide is moving currently, and how the landslide may move in the future.

Results: Mapping using lidar delineated structural features and four landslide fault-bounded kinematic elements that indicate differential movement since the initial development of the landslide. In comparing these structures to landslide deformation measured between 2020-2022, some deformation events align well with the kinematic boundaries inferred from mapping, while others indicate that new kinematic relationships have formed over time. Several lines of evidence suggest that the Barry Glacier is acting as a partial buttress to the slope, and that glacier thinning and movement impacts deformation of the slope above it, causing valley walls adjacent and upslope from the glacier to move differently than how they have in the past. Thus, actively deglaciating slopes are sufficiently dynamic that we cannot rely solely on one set of static maps of structures and kinematic elements for predictive capability. Rather, multi-temporal maps and long-term surveillance are needed to fully understand the structural and kinematic evolution of rapidly changing unstable paraglacial valley walls.

Conclusions: We conclude that when considering the relative stability of large, paraglacial, deep-seated rock landslides, the geomorphological past is not necessarily the key to the future. Understanding paraglacial and climactic forcing factors will help us make more accurate predictions of future landslide movement. With continued deglaciation in the Barry Arm and other fjords in southern Alaska, these remote but far-reaching slope instability hazards may become more prevalent.

PARAGLACIAL LANDSLIDE RESPONSE TO GLACIER DEBUTTRESSING IN SOUTHERN ALASKA

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Climate-change-driven glacier loss has far-reaching implications for the biology, hydrology, and topography of the regions in which glaciers exist. One consequence is the destabilization of paraglacial slopes as the buttressing force, or the support provided by the glacier, changes and eventually decreases to zero as glaciers dwindle. Recent work shows clear correlations between glacier retreat and slope destabilization (e.g., [1], [2]). However, the processes governing this buttressing, the amount of support glaciers can provide, and to what extent glacier retreat is responsible for landslide mobilization is still poorly understood, yet critical for characterizing the hazard potential of paraglacial landslides.

Here, we investigate eight large (roughly 20 to 500 million m3) paraglacial landslides in southern Alaska (see Figure 1). Geomorphological evidence suggests these are particularly active instabilities which, compounded with southern Alaska experiencing some of the fastest glacier retreat worldwide, makes this area especially interesting [3]. Additionally, many of the retreating glaciers are leaving behind deep ocean fjords, where landslides entering the water can lead to destructive tsunamis. The selected landslides range from those that are decoupled from the glacier to ones which have already experienced a catastrophic failure, and includes landslides undergoing active debuttressing through glacier thinning and retreat.

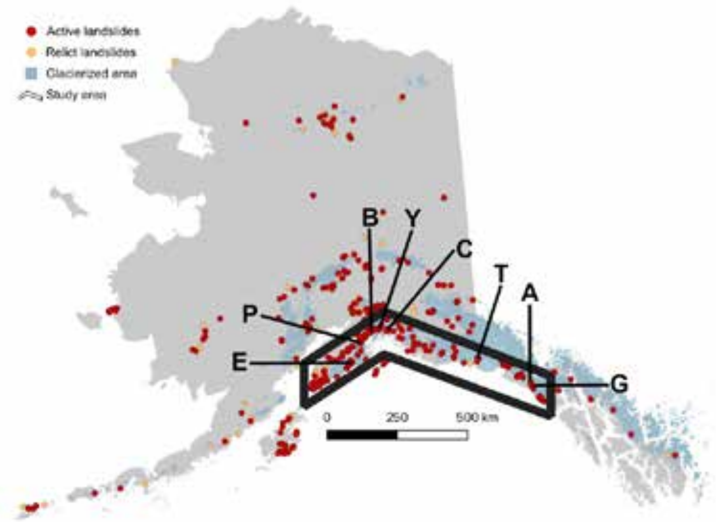

Fig. 1: Overview of Alaska landslides with individual study sites labeled by letters. Landslide locations are from the inventory of B. Higman [4]. Glacierized area (in blue) is from the Randolph Glacier Inventory [5].

We reconstruct the deformation history of the eight sites using Landsat and Sentinel images from the 1980s to present, and process the images with a digital image correlation software [6]. We compare slope displacement throughout time with ice thinning rates, ice velocities, the proximity of the landslide to the glacier terminus, precipitation, temperature, and seismicity. We create a standardized dataset, allowing for comparison of the various factors and determination of their relative impacts, and thus better constrain the critical processes for debuttressing.

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ANTICIPATING HIGH ALPINE PERMAFROST ROCK SLOPE FAILURES DURING PARAGLACIAL TRANSITION BY USING A ROCK-ICE-MECHANICAL MODEL

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As we observe rapid retreat of glaciers and degradation of permafrost in the Alps, previously stable rock slopes are being exposed to new paraglacial conditions. Given geological predisposition and the legacy of past glaciations, these rock slopes may now reach critical states close to failure. While the effects of permafrost degradation on rock mass strength are now investigated in laboratory studies, the transfer of a model explaining these processes at slope scale remains a challenge. We derived a conceptual rock-ice-mechanical model taking into account changing rock mass characteristics such as compressive and tensile strength reduction of intact rock and varying shear strength of joints upon permafrost degradation. By applying the model to the well-studied rock mass failure of Bliggspitze (3454 mamsl, AT), we validated it according to pre- and post-failure topography and field observations. Using information from geophysical measurements, surface temperature loggers, field evidence such as ice-filled fractures and mapping of springs, we derived the distribution of permafrost at the field site. Simulating permafrost thaw and retreat to higher altitudes, the rock-ice-mechanical model is capable of explaining the creation of the basal shear plane preparing the pathway from a stable to critically stable to finally unstable slope. The rock-ice-mechanical model proves to be a powerful tool for understanding past failures, assessing current rock slope stability and predicting future failures during the paraglacial transition phase.

RELIABILITY AND REPEATABILITY OF GEOELECTRICAL SURVEYS: A MULTI-METHOD APPROACH TO DECIPHER PERMAFROST AND FLUID FLOW IN FRACTURES

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Purpose: Rising air temperatures cause dramatic changes in the thermal and hydrostatic state of mountain permafrost. These changes critically affect the rock slope stability, putting high-alpine infrastructure at increasing risk. To reduce costly repairs or failures, an improved process understanding of permafrost dynamics is needed. Electrical resistivity tomography (ERT) has been used in many studies to detect changes in the ice and water content. However, challenges and limitations due to water presence in active layer clefts of permafrost bedrock remain poorly investigated.

Methods: Here we present a multi-method approach using three geophysical techniques and borehole temperatures for long-term monitoring of the subsurface properties of the steep rock wall below the Kitzsteinhorn cable car station (AT, 3.017 m a.s.l.). Automated continuous ERT measurements between February 2013 and February 2014 provided detailed knowledge on the annual and short-term hydrological and cryostatic changes. In the summer of 2022, the ERT was repeated and complemented by ground penetrating radar (GPR) and seismic refraction tomography (SRT) to better decipher subsurface dynamics. Additional laboratory investigations were carried out to quantitatively establish the relation between electrical resistivities, p-wave velocities, and temperature.

Results: Laboratory calibrations showed a frozen temperature-resistivity gradient of 53.6 ± 8.9 kΩ/°C and a threshold between frozen and unfrozen conditions of p-wave velocities at 6.2 ± 0.2 km/s. Field ERT raw data show high quality in terms of data stability. High resistivity values and dense reflection patterns can be associated with dry bedrock in the upper active layer, while low values and low reflection patterns are indicative of water influenced areas. According to borehole temperatures and p-wave velocities, frozen conditions are to be expected at depths of up to 4 m, which is not clearly represented by the GPR and ERT measurements.

Conclusions: The joint interpretation demonstrates for the first time that the detection of frozen bedrock by geoelectrical surveys is limited by its sensitivity to cleft water in the upper layers. This study helps to highlight the potential of ERT monitoring to detect high critical hydrostatic changes and thus to further improve risk assessment of infrastructure at high altitudes.

MONITORING PERMAFROST-AFFECTED ROCKWALLS, AN APPROACH COMBINING PERMAFROST MODELLING, GEOPHYSICAL SURVEYING AND RUNOUT SIMULATIONS. THE CASE OF ETACHE ROCKFALL (SAVOY, FRANCE)

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Permafrost-affected rockwalls are highly sensitive to rapid climate change, sometimes leading to rock slope failures threatening human lives and activities. Many studies have demonstrated a link between permafrost degradation and rockwall instability, but there is still a need to document destabilization events to improve the understanding of triggering and propagation mechanisms and to develop relevant approaches for hazard assessment.

For this purpose, our study investigates the rockfall / little rock-avalanche (c. 229,000 m3) that occurred in the Vallon d'Étache (Savoy, France) on June 18, 2020, after several days of heavy precipitation. The event occurred upstream of a farm, parking lot and hiking trails, without causing property damage. Ice-coating and liquid water in the rockfall scar suggest the presence of permafrost at the location of the scar, but its local distribution and its role in the triggering of the event remain to be confirmed. The rockfall deposit has been only slightly remobilised since the event, which makes it an ideal site to study the propagation characteristics.

The aims of this study are to (i) decipher the possible role of permafrost in the triggering of this event and (ii) to model its propagation by combining various in-situ measurements, field observations and numerical models in order to provide relevant data and information for the research community interested in permafrost and rockfall hazard assessment.

To do so, we first combined ground surface temperature monitoring to describe the thermal regime of the site, numerical modelling of permafrost evolution to assess thermal condition prior to the failure, energy balance modelling to estimate possible water input from snow melting and rainfall, geophysical surveys (ERT, Electrical Resistivity Tomography) interpreted with a petrophysical model developed from laboratory testing on local rock samples to gain insight on the permafrost distribution around the scar. Then, 3D topographical models acquired by photogrammetry are used to obtain high-resolution DEMs in order to measure the scar and deposit volumes, and to provide consistent inputs for runout modelling. The runout modelling leads to describe the propagation characteristics, and helps to understand if the volume of the rock slope failure has been released in a single event or in several ones.

This multidisciplinary approach brings a detailed description of the thermal conditions and dynamics that may have been involved in the triggering of this event. It also provides some depth-averaged flow simulations to model the runout characteristics of the Vallon d’Étache rockfall.

MULTI-CRYOSPHERIC-HAZARD SUSCEPTIBILITY MODELING IN SVALBARD: TESTING SPATIAL TRANSFERABILITY TECHNIQUES OF SLOPE FAILURES OCCURRENCE PROBABILITIES IN PERMAFROST DEGRADED SOILS

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Purpose: Traditionally, mid-latitudes have captured most of the attention and efforts dedicated to modelling earth surface processes via data-driven models. Unfortunately, the same cannot be said for the high latitudes' counterparts and specifically for peri-arctic and arctic regions. Recent effects of climate changes are inverting this tendency though, with permafrost-rich landscapes becoming more and more susceptible to multiple cryospheric hazards such as retrogressive thaw slumps, thaw slumps and thermos-gullying. These processes are particularly threatening as they can quickly contribute to land degradation, affecting human infrastructure and heritage in these extremely delicate environments. For this reason, some of the techniques that have become commonplace at lower latitudes and never actually tested close to the poles, are being developed, implemented and tested to understand how permafrost-related hazard can develop. This is of fundamental importance especially envisioning simulation routines for specific climate scenarios.

Methods: We initially mapped retrogressive thaw slumps and thermos-gullies in two large sectors of Svalbard archipelago. These two areas constitute a large portion of the Svalbard landscape, not permanently covered by ice or snow. As a result, high-resolution optical images have been interpreted for mapping cryospheric hazards and generate four separate inventories, two for each hazard type and two for each test site. From these, we trained four separate susceptibility models and test their transferability from one area to the other. This experiment is meant to retrieve predictive performance to be compared against site specific results. Our assumption is that, if this procedure is indeed possible, then transferring the predictive equation over the whole Svalbard territory where no inventories are available is also possible.

Results: Our transferability test showed interesting results with the two areas being more similar than expected despite their distant locations and landscapes. These results are still in their preliminary phase though and further improvements are expected by November 2023.

Conclusions: Transferring susceptibility models from different areas in Svalbard is a viable solution and its importance goes beyond the limits of this experiment. In fact, a number of coastal infrastructure and cultural heritage is currently threatened and this situation will only worsen with time. For this reason, being able to regionalize the prediction over the whole archipelago is of particular relevance to understand which action can be taken to preserve important groundwork. Another equally, if not more important conclusion is that if our models are stable and similar enough to be transferred across space, it should be possible to do the same across time.

SESSION 4.6

LANDSLIDES IN URBAN ENVIRONMENTS (part I)

INTERPLAY BETWEEN URBAN EXPANSION AND NATIONAL HYDRO-GEOMORPHOLOGICAL EMERGENCIES AT MUNICIPALITY LEVEL IN ITALY

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Purpose: Climate change and urban expansion are contributing to a considerable increase in catastrophic atmospheric and hydro-geomorphological events, which cause significant damage to urban and social fabric. This work focuses on compiling a national dataset of municipalities and provinces affected by recent hydro-geomorphological disasters for which a state of emergency was declared. The general objective is to analyze the interconnections between urban expansion and the recurrence of disasters at the municipality level.

Methods: Initially, we focused on building the dataset, also thanks to the collaboration with the Italian National Civil Protection Department, from which the data relating to national states of emergency and surveys carried out were obtained. The database consists of sets of every municipality and province hit by a critical event and included in the national state of emergency, which suffered damages and obtained subsidies for reconstruction. Afterwards, we selected a series of state-of-the-art indicators of hydrogeological hazard or risk, and we tested their correlation with the recurrence of disasters on a municipality basis. The last focus of this work was the soil consumption trend in areas at risk, starting from 2013 until now, we analyzed the increase or decrease for each municipality hit by a critical event to better comprehend local territories' policies and how they face catastrophes.

Results: We discovered that in Italy, during the last ten years, there had been more than one hundred events that have required the intervention of National Civil Protection, with the declaration of a national state of emergency and the funding of interventions for first aid and restoration. Among every correlation between risk-related variables and hit municipalities the best was found between months of emergency and the amount of urbanization in areas at medium hydro-geological risk. Lastly, taking into account this information, the study focused on soil urbanization trends: it was found that in each municipality the trend kept increasing at the same rate despite damages and economic losses.

Conclusions: This work showed how urban expansion is deeply linked to hydro-geomorphological emergencies. Urbanization trends for each municipality highlighted how local administrations, despite damages, don't change their policies.

URBAN LANDSLIDES: HISTORICAL AND RECENT LANDSLIDE DYNAMICS OF THE ISTANBUL MEGACITY

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Under the influence of anthropogenic changes, urban areas like the Istanbul megacity are suffering from intense population pressure with an increase in urbanization and construction. Such an important city in human history is also a place where, major landslide problems are observed. The spatial distribution and characteristics of these landslides in this city, which is expecting to face with a major earthquake in the near future, have not been focused on the interaction between anthropogenic disturbances and surface processes. Since 2022, different geoscience projects initiated by Istanbul Metropolitan Municipality have started investigating the secondary hazards awaiting this densely populated city after a potential earthquake. In this respect, we conducted a detailed landslide assessment for the entire Istanbul city using available LiDAR and multi-temporal optical aerial photographs. As a result of this assessment, we mapped 17764 landslides of different sizes and types. We exposed that the landslides are concentrated in specific lithologies, especially mostly in Late Oligocene and Miocene units. Moreover, we revealed that the legacy effect of paleo-landslide complexes plays an important role in the reactivation of many deep-seated landslides. We have found that several of these landslides were reactivated due to construction and infrastructure problems. We conclude by highlighting that this new and comprehensive landslide inventory for Istanbul mega city will contribute to decision-makers in planning urban areas with low vulnerability and high resilience by identifying areas with risk in terms of existing settlement and infrastructure.

LANDSLIDE RISK REDUCTION IN MEDEA CITY

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Purpose: Algeria and more particularly the north part of the country is prone to many natural hazards such as earthquakes, floods and landslides…etc. Landslides have affected many cities situated in mountainous regions of that part of country. Among these cities, Medea city, which is about 70km oust of Algiers, has encountered many landslides events during the last decades. In order to mitigate the effect of these landslides, the national authority which represented by the Department of Urban planning, Architecture and Construction (D.U.A.C) of Medea has launched a landslide assessment study of the northern flank of Medea which covers an area of 767.25 Hectares.

Methods: The study was based on the analysis of fourteen profiles. In each profile there were five borehole, two borehole were equipped with piezometer and three boreholes were equipped with inclinometer. The topography survey of each profile was mad using drones.

Results: A lot of shallow soil movements were observed due to the rise of the water table which is fed by rains and leaks in the water supply networks.

Conclusions: The studied area was set as vulnerable area towards landslide hazard and it was decided to find an economical solution to lessen this hazard in order to use it for the urban expansion of Medea City.

UNSTABLE GROUND: ASSESSING URBAN LANDSLIDE RISK IN UTTARAKHAND, INDIA

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Purpose: Joshimath is a town in Uttarakhand, India, that has experienced a crisis in the past year. The town, located at an altitude of 1,900 meters, serves as a gateway for the Badrinath pilgrimage and is a base for treks and expeditions in the Himalayas. However, it is situated on top of a large landslide deposit, and in recent years, it has experienced an increase in sliding that has damaged over 850 buildings. Consequently, many of these buildings are being demolished, causing significant economic losses to the community. While the deformation rate has increased dramatically since late 2022, our InSAR analysis reveals that most of the town has been moving for years, with some areas sliding faster than others. The unstable area extends beyond the most settled areas. Uttarakhand, located in northern India and bordering Tibet to the north and Nepal to the east, is situated in the Himalayan mountain range. It is known for its steep and unstable slopes, high rainfall, and high seismic activity. As a result, the region is prone to landslides and earthquakes, which pose a significant threat to the safety and well-being of the people living in the area. Most landslides in the region are triggered during or immediately after the monsoon season, i.e., between June and September, but many are active throughout the year. Joshimath, located in the Higher Himalaya near the Main Central Thrust (MCT), is not unique. Many townships in the Greater and Lesser Himalaya have active landslides, including Mussoorie (30°27’35"N; 78°03’50"E), Nainital (29°23"31”N; 79°27"15”E), Uttarkahshi (30°43’36"N; 78°26’07"E), Semi-Guptkashi (30°31’29"N; 79°05’04"E), Bhatwari (30°49’05"N; 78°37’07"E), Dharchula (29°50’50"N; 80°32’13"E), and many others. Most of these townships are located in the Lesser Himalaya or in the vicinity of the MCT zone. Slope deformation in the form of creeping movement has been observed for quite some time. However, many slopes in the area have failed due to more frequent extreme weather events caused by climate change.

Methods: To understand the underlying forces driving landslide motion, we conducted a regional InSAR study using all the Sentinel-1 images covering the state of Uttarakhand for the period 2018-2023. First, we systematically derived active deformation areas and compared them with an inventory of 3303 active landslides in the state. We explored the spatiotemporal response patterns of active landslides to annual precipitation cycles and classified them by their state of activity. Finally, we selected several urban areas with active deformation throughout the year for further analysis and comparison with field observations.

Results: Our study highlights the urgent need for effective land-use planning and mitigation efforts to reduce the risk due to landslides in towns throughout the Himalaya, similar to Joshimath. In addition, the results of this study can be used to develop effective strategies to ensure the safety of the people and their properties and to identify areas in Uttarakhand in need of the development and implementation of effective monitoring and early warning systems.

LANDSLIDE AND DEBRISFLOW HAZARD ASSESSMENT IN TBILISI (GEORGIA)

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In the last decades of the XX century, protect the population from geological hazards, to maintain land and safe operation of the engineering facilities has become the most important social - economic, demographic, political and environmental problems for the whole world. As it is known, geographically Tbilisi has a very convenient location and is not only the capital of the country, but also a hub of the transit corridor. However, in the conditions of complex morphological and geological environment, as well as high pressure of man-made load, geoecological complications have reached a critical level and human engineering-infrastructural activities are growing even more.

Based on the analysis and generalization of fund (historical) materials, laboratory and field studies, the research evaluates the combination of factors that determine the tendencies of geological processes. Among the geological hazards on the territory of Tbilisi, landslides, debris/mudflows and rockfall/rock avalanche processes are worth mentioning. These processes are widespread, causing great material damage to the city's infrastructure and, most tragically, often resulting in human casualties - according to available data in the twentieth century and the last two decades, landslides in Tbilisi have killed 170 people. Surveys in the study area revealed 655 landslides of various scales, 55 rock-fall areas, as well as more than 50 debris/mudflow gorges.

The research evaluates large-scale landslide, rockfall, rock avalanche areas, debris/mudflow watersheds and gives recommendations for protective measures. GIS database was created and based on all this information, hazard zoning map at 1:25 000 scale was compiled. Geological maps published in the last century were revised, as well as various thematic (elevation, slope and aspect) maps were compiled. Research classifies the protective adaptation measures, which are necessary to mitigate or completely eliminate the processes, according to their type and genesis.

THE LARGE SAN VITO ROMANO (CENTRAL ITALY) LANDSLIDE SYSTEM THREE-DIMENSIONAL GEOLOGICAL-TECHNICAL MODEL

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Purpose: On large landslide areas, two-dimensional and three-dimensional geological-technical model realization require several numbers of subsurface data. We investigated a complex landslide system located in the urban area of San Vito Romano, Central Italy, 40 km east from Rome where a large number of boreholes, piezometers and geophysical surveys are available. The purpose of this work is the characterization of the San Vito Romano landslide in order to create a geological-technical model to support local authorities in risk prevention and civil protection activities. The geological context is characterized by a Tortonian sequence of turbidite deposits, constituted by marls with arenaceous intercalations, forming a monocline with 15-20° dip-direction eastward, parallel to slope inclination. Moreover, a complex hydrogeological system features the groundwaters. The landslide has a spatial extent of about 0.5 km2 and it has been studied for more than 25 years. It affects San Vito Romano's new town (built from the 1960). Significant structures damages have been detected over time and some buildings are currently unusable. From a geomorphological point of view, the village is located along a cuesta's less steep side.

Methods: A multitude of technical reports were carried out in this area during the last decades: geological surveys for building projects, geotechnical surveys for landslide monitoring planning, academic studies and field survey to understand the geomorphological slope evolution, hydrogeological and geophysical survey. All the available surveys were censored in order to create a large database with all information from 80 linear and punctual surveys. Therefore, a boreholes surveyed simplified interpretation was carried out. Stratigraphic and geotechnical data with seismic and geoelectrical data, landslide material body was characterized. All available data has been processed in GIS environment. 15 cross sections were realized allowing a two-dimensional landslide system interpretation. Finally, the cross sections were correlated to create a single three-dimensional subsurface model.

Results: The San Vito Romano landslide has been interpreted as a large slow-moving (less than 1 cm/yr) rock translational slide evolving along medium-deep sliding surface. The model shows the presence of almost three surfaces of rupture at different depth (up to a maximum of 48 m) and the geological framework of the wide translation slide.

Conclusions: These investigations provided scientific support to the new San Vito Romano urban planning, in order to define the instability areas and the local geomorphological hazard. Thanks to in-depth subsurface studies, landslide area has been enlarged compared to previous studies. In this way it was possible to regulate new building construction.

Finally, the geological-technical model was useful in helping local authorities and non-experts to plan and manage the risk mitigation works.

GEOTECHNICAL ANALYSIS OF THE SUSCEPTIBILITY TO TRASLATIONAL SLIDING EXPERIENCED BY THE 'EL RINCÓN' ROCK MASSIF ON A HIGH CAPACITY HIGWAY SITUATED IN THE CAPITAL OF GRAN CANARIA

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Purpose: The analysis of the fracturing experienced by the “El Rincón” rock mass aims at: defining the morphogenesis of the numerous types of discontinuities which undercut a slope of 200 m in high; establishing the degree of influence that each set of discontinuities has on the slope instability process; numerically modelling the progression of the slope; and assessing the associated hazards.

Methods: The study combines a geomorphological analysis, topographic and photogrammetric monitoring and numerical modelling.

Results: The analysis of the fracturing experienced by “El Rincón” rock mass (between 1944 and 2023) shows 3 types of discontinuities: a NE-SW fault system that creates a horst-graben; a total of 10 NE-SW open cracks that break the scarp; and numerous ENE-WSW joints that undercut the slope. The origin of the fractures is related to the NW-SE distensive regime associated with the volcanic intrusions of the Post-Roque Nublo Group. Monitoring of the fractures (1962-2023) shows a maximum displacement of the slope of 14 mm/yr, an average crack elongation of 2.7 mm/yr, a maximum crack depth of 51.8 mm/yr and a maximum separation between crack lips of 157 mm/yr. The topographic analysis leads to the existence of a slow and complex landslide that alternates a translational and rotational movement and whose effects are amplified by the areolar erosion. This paper also identifies the landslides that can develop on “El Rincón” rock mass and their consequences on the GC-2 highway, located at the base of it. Although limit equilibrium methods show the slope is currently stable, two rock blocks were considered susceptible to long-term landslides due to water saturation: one in the middle of the slope and one at the crest of it. Rockfalls probabilistic analysis shows that rock blocks are not expected to reach the GC-2 highway, but they will tend to accumulate in the dejection cones found at the bottom of the slope.

Conclusions: A large block is expected to be instable before 2075. Its estimated dimensions (between 103 m3 and 448 m3) depends on the basal plane of failure considered. This crest block sliding seems more likely since it only requires pyroclastic saturation and is favored by the progressive opening of a subvertical crack that has been monitored for more than 40 years.

SEISMICALLY-INDUCED SLOPE INSTABILITY IN SAN SALVADOR MUNICIPALITY (EL SALVADOR, CENTRAL AMERICA): THE SEISMIC SCENARIO OF THE 13 JANUARY 2001

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Purpose: The objective of this research is focused on the co-seismic slope instability induced by the seismic activity felt in El Salvador country. This study compares the calculation of the permanent displacement (D) values induced by January 13, 2001, earthquake through GIS-based equations in San Salvador urban area (MASS) and the landslide inventory drawn by Mercurio et al. (2021) from the aerial images taken by the CNR (Centro Nacional de Registros - Instituto Geográfico y del Catastro Nacional) in the aftermath of the main shock.

Methods: A common method to calculate the permanent displacements induced by seismic events consists of using regression equations drawn from worldwide databases of records of seismic accelerations. These equations use parameters representative of the seismic solicitation and the dynamic soil resistance to estimate the expected seismic displacements at the site of interest. In this study, two formulations have been selected to draw maps of D triggered by the 13 January 2001 earthquake within the QGIS environment:

$$\text{Log}(D) = 0.561 \cdot \log(Ia) - 3.833 \cdot \log(kc/PGA) - 1.474 \pm 0.616 \text{ (cm)} \quad (1)$$

$$\text{Log}(D) = -0.22 - 2.83 \cdot \ln(kc) - 0.333(\ln(kc))2 + 0.566 \cdot \ln(kc) \cdot \ln(PGA) + 3.04 \cdot \ln(PGA) + 0.244 \cdot \ln(PGA)2 + 0.278 \cdot (M - 7) \pm 0.67 \text{ (cm)} \quad (2)$$

Eq. (1) was proposed by Jibson (2007), Eq. (2) by Bray and Travasarou (2007), where Ia is the Arias Intensity; kc is the critical seismic acceleration; PGA is the peak ground acceleration; M is the Magnitude. The spatial interpolation of PGA and PGV have been performed by the Digital Terrain Model of 5x5 m2 provided by the Ministerio de Medio Ambiente y Recursos Naturales Office.

Results: In the maps (Figure 1) the landslides inventoried by Mercurio et al. (2021) triggered by the 13 January 2001 earthquake are reported in black. As can be noted, Bray and Travasarou's equation shows higher permanent displacement values than Jibson's one. The crest of the whole Balsamo range between Las Colinas and Los Chorros shows D varying from 20 to 50 cm.

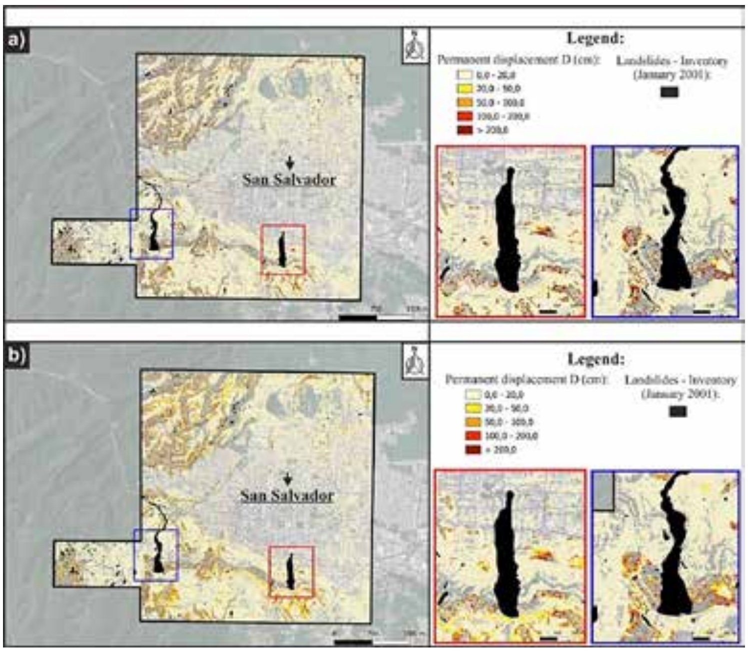

Fig. 1. Permanent displacement maps were calculated at MASS by: (a) Jibson (2007) and (b) Bray and Travasarous (2007) regression equations.

The portions of the Balsamo range where the landslides actually occurred show higher D values, from 50 to 100 cm.

Conclusions: In this study, we applied Jibson's and Bray and Travasarou's equations to predict co-seismic permanent displacements triggered by the 13 January 2001 earthquake in MASS. Both equations show high D values where landslides occurred although Bray and Travasarou's equation estimates high permanent displacements at larger areas.

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BACK-ANALYSIS OF THE CO-SEISMIC LAS COLINAS FLOWSLIDE AT SANTA TECLA (SAN SALVADOR, EL SALVADOR)

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Purpose: The aim of this study is to back-analyse the Las Colinas complex flowslide (in Santa Tecla, El Salvador), triggered by the 13 January 2001 earthquake (7.6 Mw). This event occurred about 100 km from Santa Tecla (along the Central America Trench) and at a depth of 32.1 km. In this study, the permanent displacements along the Las Colinas slope were calculated using both empirical and rigorous Newmark's method (Newmark, 1965).

Methods: Di Clemente (2022) first performed the Gis-based permanent displacement analyses through two empirical equations by Jibson (2007) and Bray and Travasarou (2007). We performed the stability analyses of the Las Colinas slope using the Finite Element Method and the Limit Equilibrium Method to apply the Newmark method through GeoStudio code. The finite element analyses used the equivalent linear constitutive law for dynamic simulations. The horizontal accelerograms of two stations near the area where the landslide occurred were used as input signals. Then, we estimated the permanent displacements by the rigorous Newmark method along the sliding surface.

Results: Figure 1 shows the slope section inspired by Crosta et al. (2005) and Table 1 lists the formations involved with their physical and mechanical properties from the litho-technical characterizations of Lotti and Associati (2001). The dynamic analysis showed a shear stress concentration along a similar sliding surface found by Crosta et al. (2005). Then, the Newmark method was applied along this latter sliding surface. The permanent displacements between 20- 90 cm were calculated from accelerograms recorded during the January seismic event. This amount of displacement can trigger a landslide. Similarly, the GIS-based Bray and Travasarou's equation (2007) predicted, at the crest of Las Colinas slope, permanent displacements between 20-50 cm. These values match with rigorous results, although higher than Jibson's one (2007).

Conclusions: Comparison between the permanent displacements calculated through empirical equations and rigorous Newmark method highlights that Bray and Travasarou's equation is more predictive than Jibson's for Las Colinas landslide. The numerical approach confirms that Las Colinas landslide triggers displacements of 20-90 cm.

Table 1: soil unit mechanical properties.

Units	Dry unit weight (KN/m^3)	FRiction angle (°)	Cohesion (KPa)
Terra blanca	11	39	30
Pyroclasts	13	35	80
Paleo-soils	11	24	10
Brown cinders	15	33	40
Paleo landslide deposits	8	20	10
Loose pyroclasts	8	20	10
Tuffs and pyroclastic flows	18	38	200

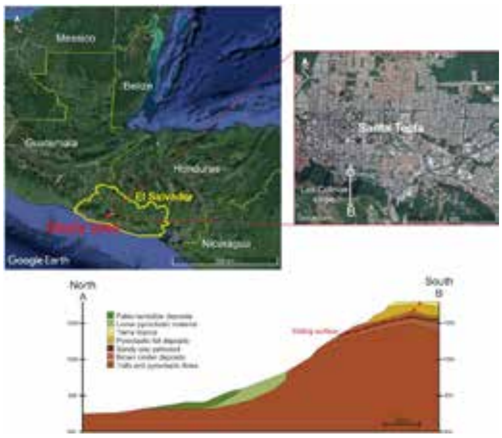

Fig. 1: location maps and slope section modeled.

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SESSION 2.3

PROACTIVE RISK MANAGEMENT BASED ON INNOVATIVE MONITORING METHODS

INTEGRATION OF SURFACE AND SUBSOIL DISPLACEMENT DATA IN THE FIELD OF SLOW KINEMATIC LANDSLIDE. THE EXPERIENCE WITH INNOVATIVE ROBOTIC SYSTEMS FOR TOPOGRAPHIC AND INCLINOMETRIC MEASUREMENT

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Purpose: In the context of monitoring complex landslides, a fundamental aspect is the possibility to describe the soil and subsoil deformation trend. As known, topographic observation alone does not allow to define exactly where the deformation develops in depth, but represents only a sum of what happen on the subsoil up to the ground. Within an intensive/extensive investigation plan, the Regional Agency for Territorial Security and Civil Protection of the Province of Piacenza (Emilia Romagna Region) has identified some landslide phenomena to be monitored in a combined way through analysis of deep-seated ground deformations and surface displacements. The first studied phenomenon is located in the municipality of Bobbio – (Gobbi hamlet) and is characterized by a very slow kinematic with a not yet well-defined depth of movements and temporal trend. The morphology of the area is characterized by numerous phenomena, in particular large-scale earthflows, causing locally damage to some of the buildings of Gobbi hamlet.

Methods: The integrated monitoring network is characterized by a robotized inclinometric system (Allasia et al, 2020) and a topographic network measured by a robotic total station. The robotized inclinometric system, installed in 21/02/2022, allows almost continuously inclinometric measurements (about 1÷3 measurements per day) for the entire length of the borehole (about 50m) using a single inclinometer probe. The robotic total station, operated since August 2020, allows monitoring the displacement of about 12 prisms installed on buildings located in the landslide area. In addition to these systems, there are also a series of automatic piezometers.

Fig. 1: Robotized Inclinometer System (on the box), topographic prism (empty circle) and piezometer (filled circle).

Results: At present, the robotized inclinometric system detected no significant movements in depth, but only small deformations on the surface that cannot be attributed to the landslide phenomenon. At the same time, the robotic total station shows movements in the order of few cm only on some specific buildings, which might suffer from local instability conditions.

Conclusions: The integrated monitoring network has allowed a first series of considerations to be made regarding the deep behaviour compared to what was observed on the surface. The possibility of having almost continuous monitoring on the surface/depth can also allow to evaluate any accelerations in concomitance with many scenario (snowmelt, rain, increased interstitial pressures). These results will also be used to better focus the design of mitigation works and to control their effectiveness.

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INTEGRATED MONITORING FOR LANDSLIDE RISK MITIGATION AND FOR THE DEVELOPMENT OF SUSTAINABLE TORRENT BARRIERS: THE CASE OF THE HAHNEBAUM LANDSLIDE

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Purpose: The Hahnebaum landslide is located in the upper Val Passiria (BZ) and can be defined as a complex phenomenon with secondary ones. The main critical issues are related to the valley damming in case of a slope collapse and interruption of the international road SS44Bis. In the early 15th century, a partial slope collapse was recorded with valley occlusion, lake formation, collapse of the dam, causing ~400 victims. As part of the reduction of landslide toe erosion by the Passirio river, a large number of partially deformable torrent barriers were built to absorb also a part of the landslide thrust. These types of barriers, partially free for the translation (orthogonal to the river), have recently been built to replace the previous rigid ones that went out of service due to high deformations.

Methods: In order to monitor the state of landslide activity, a complex monitoring network of surface, deep and infrastructure deformations was created in collaboration with the Autonomous Bolzano-Province. This paper shows some results obtained by a robotized inclinometer system for measuring deep-seated ground deformations and by a deformations/displacements measurement of some Passirio river torrent barriers. The torrent barriers are under the direct influence of a slow-moving landslide, which have an impact on the loads on the structure. The aim of the geotechnical measurements at the torrent barriers is to determine creep pressures due to moving landslides and to compare these with the data from monitoring. For this purpose, various sensors were installed at the structures, which measure strains, pressures and displacements. The geotechnical measurements at the torrent barriers and the data from the robotized inclinometer system will provide the basis for the development of new types of barriers, that are sustainable against slow-moving landslides and less vulnerable.

Results: The preliminary results allowed to identify two main sliding surfaces located at 28.5m depth and 7m depth with higher cumulative deformation rates at 27m depth (18 mm/year). The kinematic observed confirms the complexity of the scenario probably also related to geological/geomorphological constrains induced by opposite slope in such a narrow valley. The sensors at the torrent barriers have been in operation and transmitted with remote transmission since fall 2022.

Conclusions: In the management of highly dangerous landslide areas, the role of multi-instrumental monitoring networks is strategic for civil protection and infrastructure maintenance/preservation. These systems must focus on several aspects of the landslide in order to simultaneously acquire parameters on the main phenomenon but also on the infrastructures involved in case of slope failure.

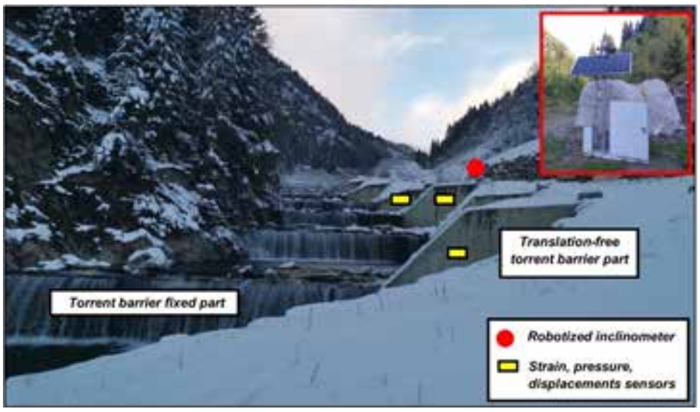

Fig. 1: Main components of integrated monitoring network of Hahnebaum landslide.

PROACTIVE LANDSLIDE PREVENTION IN QUICK-CLAY AREAS USING MACHINE LEARNING AND GIS ANALYSIS

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Quick clays are marine clays deposited under the ice age that due to its intern structure and geochemical interactions, when overloaded they are prone to collapse, causing devastating landslides. Many of the most populated areas in Norway are built on these marine deposits and in recent years, we have seen several catastrophic landslides caused by quick clays, the most recent one at Gjerdrum in December 2020. This highlights the urgent need for proactive detection of high-risk areas.

In areas with quick clays, erosion and other terrain changes along ravines and water courses can lead to small slides that can be a precursor to larger, more devastating landslides. Identifying these terrain changes in a timely and efficient manner is crucial for mitigating the risk of larger retrogressive quick-clay landslides.

In this article, we propose the use of image segmentation and machine learning techniques to identify small landslides and terrain changes along water courses in quick clay areas. We make use of digital elevation models (DEMs) derived from lidar data to extract elevation, slope, and curvature changes over time. These data are then fed into a convolutional neural network (CNN) that has been trained to identify the terrain changes that can be a sign of or lead to a deterioration in slope stability.

The results of our study demonstrate that the proposed method can identify small landslides with efficiency. The use of image segmentation and machine learning techniques allows for the automation of the process, reducing the time needed for field inspections. Furthermore, our approach can detect small landslides that may not be visible on traditional maps or aerial imagery, in areas where people seldom walk due to steep, highly vegetated hills.

Once we identify these changes, we use a GIS tool and topographic criteria to rank them by their potential consequences. Specifically, we calculate a maximum potential landslide area based on the terrain's characteristics such as global height and slope, which helps us assess the potential impact of a landslide in terms of, for example, the number of affected homes.

Through this holistic approach to landslide risk prevention, we can prioritize areas for further geotechnical and geophysical investigations, implement targeted strategies like slope stabilization and erosion protection, and other measures to prevent larger, more destructive landslides from occurring. This will help to protect communities and ensure the safety of residents in at-risk areas, minimizing the potential loss of life and property damage caused by quick clay landslides.

ANSIP_ICS: A 3D SCENARIO ILLUSTRATION PLATFORM FOR PRELIMINARY LANDSLIDE SCARP ASSESSMENT

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Purpose: We are going to present a 3D advanced scenario illustration platform (ANSIP) in which the landslide scarp can be preliminarily estimated, and the resulting objects are displayed via animated 3D graphics. With the presented system, users can interact with 3D scenes in a browser to select the area prone to landslide when the digital elevation model (DEM) of the topography is available.

Methods: The platform is based on OpenGL and Application Programming Interface (API). The plausible failure surface is approximated in the shape of an Idealized Curved Surface (ICS, Tai et al., 2020). In the selection mode, four points on the boundary of the target area are assigned in the browser, and the initial reference ellipse is constructed. With respect to the assigned conditions (delineated potential area, failure depths, the released volume of mass, etc.), the candidate ICSs are constructed by an ellipse-referenced approach (ER-ICS, Ko et al., 2021a). The best-fitted ICS is selected through the genetic algorithm (GA) by translating and rotating the reference ellipses (Wang et al., 2022). In addition, the manipulation treatment introduced in Wang et al. (2022) is utilized to isolate some redundant portion(s) of the ICS-covered area for excluding the unexpected regions in the neighborhood of the target area.

Results: The construction of the ICS for each reference ellipse is developed with CUDA Toolkit for high-performance GPU computation. Together with the GA approach, the computational duration can be reduced from tens of hours to several minutes, depending on the set parameters (translation range, generations in the GA, etc.). In the ANSIP_ICS system, the parameters are set through the GUI, and the results can be examined in the 3D user-interactive browser.

Conclusions: Combining of the presented ANSIP_ICS system and a GPU-accelerated simulation tool (MoSES_2PDF, Ko et al., 2021b) facilitates a high-efficient 3D user-interactive illustration system for landslide hazard assessment, especially for the post-failure subsequent flow paths in various scenarios.

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USE OF A GROUND-BASED DOPPLER RADAR TO REGULATE TRAFFIC ALONG A ROAD CRITICALLY EXPOSED TO ROCKFALL HAZARDS

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Purpose: In 2019–2020, accelerated deformation of a highly disaggregated area of the ~30 million m3 Ruinon landslide (Central Italian Alps) has been promoting secondary mass wasting processes in the form of destabilization and fall of variably sized boulders embedded within a thick upper layer of debris. Defense structures in place at the time could not provide safety against all potential rockfall magnitudes, hence these events posed a serious threat to a road travelling along the valley floor.

Methods: We deployed an innovative ground-based Doppler radar to manage rockfall hazards in real-time at the Ruinon landslide. The instrument, which not only can detect the occurrence of a rockfall along a slope but also dynamically track its trajectory, was connected to a pair of traffic lights in order to instantly enforce an exclusion zone for approaching vehicles whenever rapid movement initiated. We therefore implemented a mostly automated alarm strategy in order to conjugate two opposing needs: preventing indefinite periods of road closure, which would result in isolation of a nearby town; and preventing vehicles from being within the area exposed to risk during the actual occurrence of a rockfall. At the end of each event, the decision to switch the traffic lights back to green or rather require a user-controlled reset was taken by the instrument based on the extent of rockfall runout (i.e., based on whether the rockfall reached the slope toe or not). The user-controlled reset of the traffic lights could be performed in situ or remotely through a dedicated web interface, where event data and footage from a network of surveillance cameras were also uploaded.

Results: Between July–December 2020, a total of 60 rockfalls were detected by the instrument and consequently caused traffic lights to be temporarily switched to red. These rockfalls ranged down to volumes of less than 1 m3. Three of them propagated far enough to reach the slope toe. Radar outputs involve a georeferenced map of Doppler shift intensity outlining the area hit by the rockfall, as well as direct estimates of runout length, runout velocity, and line-of-sight distance from the rockfall source area. After initial calibration of the instrument, a very limited amount of false alarms were caused by disturbance from intense thunderstorms. Importantly, there have been no field evidences or accounts of significant undetected rockfalls. In 2021, the activity of the landslide strongly reduced thanks to construction of surface drainage measures, and so did the frequency of rockfalls.

Conclusions: The experience gained at Ruinon highlights that ground-based Doppler radar may be exploited to accurately track rockfalls as they descend along a slope. This offers the opportunity to enhance safety along sections of transportation corridors in steep mountainous terrains that, due to local morphology and/or expected event scale, are critically exposed to rockfalls and related slope hazards. In addition to this strictly operational aspect, use of the technique may enhance our understanding of rockfall motion, frequency, triggers, and quantitative influence on the erosion of rock/debris slopes.

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MONITORING THE SURFACE DISPLACEMENTS OF A LANDSLIDE USING PHOTOGRAMMETRY, CONVOLUTIONAL NEURAL NETWORK AND CROSS CORRELATION ALGORITHMS

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Purpose: Monitoring of surface displacements is of primary importance to better understand the temporal and spatial evolution of an active landslide. Some conventional techniques, such as topographic or GPS monitoring methods, are characterized by high accuracy, but are generally spatially and temporally sparse. On the other hand, the use of techniques such as terrestrial laser scanning allows for a dramatic increase in spatial resolution, but scans are generally few in time due to their cost. This paper presents an innovative low-cost approach to measure surface displacements of landslides based on the use of digital image correlation and photogrammetric algorithms. The proposed system has the potential to continuously estimate landslide velocity trends over the entire area visible in the image, although with the disadvantage of lower accuracy than other systems.

Methods: The hardware configuration consists of one or more cameras set to shoot at predetermined time intervals adaptable to site conditions. In addition, external hardware is installed to trigger the camera shutter and automatically send the collected images to a remotely accessible FTP server. Before starting time-lapse acquisition, careful calibration of the intrinsic and extrinsic parameters of the cameras is required, as this step affects the accuracy of the displacement estimation. Once the system is properly set up, the workflow steps can be schematized as follows: (i) a sequence of multiple self-coded MATLAB algorithms is used to automatically download images from the FTP server, discard low-quality images using the GoogLeNet convolutional neural network, and correct any artifacts on the images (e.g., slight camera shake); (ii) a second GoogLeNet convolutional neural network is used to automatically select the images to be used for the monitoring tasks according to the chosen time step; (iii) a digital image correlation technique based on the cross-correlation metric allows reconstructing the displacement field, in pixels, on the 2D image plane; (iv) 3D displacements in metric units are finally obtained by projecting the 2D displacements onto a depth map of the scene, which provides for each image pixel the object-camera distance and the local orientation of the slope surface.

Results: The method was applied for monitoring the Sant'Andrea landslide (Belluno province, Italy). The photogrammetric monitoring activity was carried out during the period from May 2021 to September 2022. Automatic topographic monitoring realized by a robotic total station (RTS) was also present at the site, measuring the displacements of a specified number of targets. An initial validation of the photogrammetric technique was carried out by comparing its results with those of the RTS. Then, the results of the photogrammetric monitoring method were used to more comprehensively analyze the kinematics of the landslide, especially in areas not covered by topographic monitoring.

Conclusions: The proposed technique offers a low-cost alternative for spatial and temporal monitoring of landslide surface displacements. Despite some inherent limitations of this technique related to its dependence on weather conditions or lower accuracy compared to other methodologies, this innovative approach is capable of detecting displacements ensuring spatially distributed and dense continuous measurements.

A MODEL FOR INTERPRETING THE DEFORMATION MECHANISM OF RESERVOIR LANDSLIDES IN THE THREE GORGES RESERVOIR AREA, CHINA

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Purpose: Reservoir landslides attract wide attention as they can cause huge surge waves and other disastrous consequences. The surge wave produced by the 2003 Qianjiangping landslide, which slipped shortly after the Three Gorges Reservoir (TGR) in China was first impounded, capsized 22 fishing boats and took 24 lives. However, reinforcement structures are costly and difficult to construct, and thus many huge reservoir landslides have not been treated. Many remain in a state of continuous deformation, such that cumulative monitored displacements of several meters are now documented. Additional study of the deformation and failure mechanisms, and risk reduction strategies of these huge reservoir landslides is of great significance.

Methods: This study presents a model combined with seepage simulations to elucidate how reservoir landslides deform, using the Shuping landslide as an example. The new environmental and deformation data monitored here extend the observational period for this landslide to more than 13 years, and include results that confirm the effectiveness of a control strategy that have been implemented.

Results: A driving-resisting model is presented to elucidate the deformation mechanism of reservoir landslides, as exemplified by Shuping landslide. The displacement velocity of Shuping landslide is closely related to the variations in the level of the Three Gorges reservoir. Rainfall effects are limited in comparison, perhaps due to the low hydraulic conductivity of the slide material. Rapid reservoir drawdown produces large, destabilizing seepage forces in the slope of the slide mass, as evidenced by large increases of its displacement velocity. In contrast, rising reservoir levels reverse the direction of the seepage force, improving slope stability and decreasing the displacement velocity. The buoyancy effect on the resisting section decreased the slope stability when the reservoir first rose to 135 m ASL, but this effect has diminished as the reservoir has attained higher levels that buoy both the driving and resisting sections.

Conclusions: Monitoring data demonstrate that the proposed model is effective to interpret the deformation process of reservoir landslide. Approaches are: 1) transferring earth mass from the driving section to the resisting section; and 2) lowering the ground water levels inside the slope by drains or by pumping during periods of reservoir drawdown. The first approach was successfully applied to the Shuping landslide and could be used to treat many other huge landslides in the Three Gorges Reservoir area.

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SESSION 5.6

LANDSLIDES, EARTH DAM AND LEVEE FAILURES DURING RECENT EXTREME PRECIPITATION EVENTS

LANDSLIDE STABILISATION: A CASE STUDY IN THE NEW FOREST NATIONAL PARK

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Purpose: On the night of 2nd November 2019, during a major storm which followed a very dry summer, a landslide occurred in the area of Nomansland, in the New Forest National Park, known as a generally flat laying area in the south of England. The landslide exposed the foundations of a detached workshop and posed a threat to the stability of the main house. The movement was also noted to continue for days, but at a much slower rate. The risk for further movements caused by the seepage of surface water in to the ground was extremely high and therefore the stabilisation of the slope was recommended on an urgent basis.

Methods: The study comprised an appraisal of the recent site history, the development of several walkovers and the undertaking of a site-specific intrusive investigation to define the ground conditions, establish the causes for the triggering of the landslide and inform the development of stability analyses based on limit equilibrium methods for the design of interventions able to stabilise the slope. The results of in-situ and laboratory tests were calibrated with reference to the post-failure geometry of the slope considering a compound-type landslide. The analyses undertaken allowed to understand that the slope could not be satisfactorily stabilised by means of a single, massive and particularly invasive intervention, as this would have required a long time for the mobilisation of cumbersome machinery and caused consequent delays in re-establishing safe conditions at the site. It was preferred, therefore, to propose a series of smaller scale interventions to favour site accessibility, to complete the site works in the shortest possible period and to simplify the insertion of the interventions within the surrounding environment.

Results: The chosen stabilisation strategy focused on both mitigating the triggering actions and increasing the resisting forces. Various options were considered at design stage, including the use of tyre bales, the construction of isolated piles, the insertion of culverts into the slope and similar, but were discarded in favour of more traditional methods not subjected to environmental approval from overseeing organisations. Drainage blankets and trench drains were proposed to avoid the rise of groundwater levels within the slope. The in-situ colluvial soils were replaced with imported lightweight aggregates and the overall slope was regraded to reduce original steepness. In addition, a stabilising berm was built at the toe of the slope reusing the excavated material. The whole slope was then reinstated with the insertion of geomaterials and the placement of suitable topsoil, to improve the resistance to shallow erosional actions and the eventual migration of fine grained materials from the topsoil into the underlying lightweight aggregates.

Conclusions: A case study was presented for the stabilisation of a landslide in loose soils. The study allowed to stabilise the slope by means of simple and well known methods providing a valid long-term factor of safety without affecting the insertion within the surrounding environment. The site is now fully reinstated and back in the availability of the owners.

PERSPECTIVE FROM 5 YEARS (2017-2022) OF WIDESPREAD LANDSLIDE EVENTS IN PUERTO RICO

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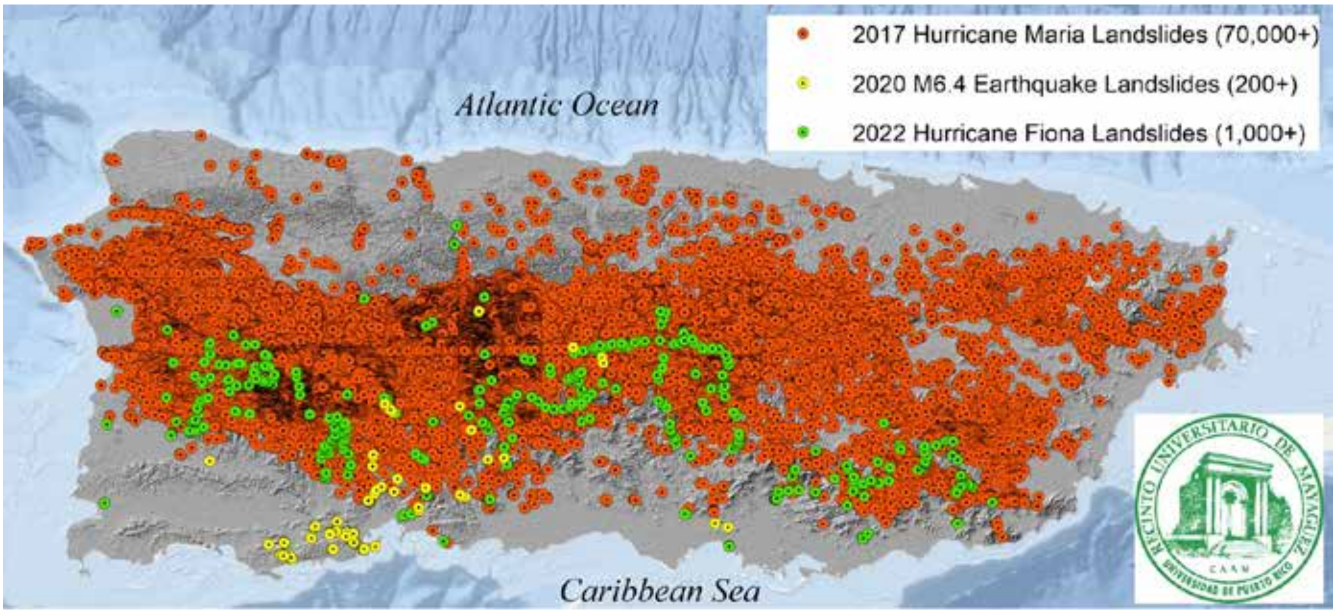
Purpose: From 2017 to 2022, the tropical island of Puerto Rico has experienced several widespread landslide triggering events. These events include Hurricane Maria (2017), a M6.4 earthquake and related seismic sequence (2020), and Hurricane Fiona (2022).

Methods: After each of these disasters, we led or co-led efforts to catalog the extent and character of landsliding sponsored by the Geotechnical Extreme Event Reconnaissance (GEER) initiative that were collaborative with several continental US universities and governmental agencies. Additional local efforts led to the creation of the "Storm-induced Landslide Impact Dynamics on Environment and Society in Puerto Rico" (SLIDES-PR) program at the University of Puerto Rico. In the absence of a local geological survey office, this project serves as the island's primary center for landslide hazard science and community engagement.

Results: Principal products of the collaborative responses to these events include a geotechnical impacts report for each event, event-specific landslide inventories, a modern high-resolution rainfall-induced landslide susceptibility map for Puerto Rico, an illustrative Spanish-language landslide guide for residents of the island, an experimental landslide forecast system built upon a network of stations installed throughout the island's rugged mountains, and a pilot LandslideReady program to certify community preparedness for landslide hazards. Secondary, less immediate landsliding effects, like freshwater reservoir sedimentation have also been studied, specifically after Hurricane Maria. These topographic and bathymetric analyses have shown that landslide-related sedimentation related to a single event is responsible for around 15 years of background sedimentation into some of Puerto Rico's most vulnerable freshwater reservoirs.

Conclusions: Puerto Rico remains inevitably and especially susceptible to landslides given its tectonic, topographic, climatic, and anthropogenic conditions. However, in the wake of the landslides brought about in the past 5 years, efforts channeled through the SLIDES-PR program have led to an improved understanding of landsliding across the island and how to convey susceptibility, vulnerability, hazard, and risk to planners, emergency managers, and the general public. As the endeavor moves forward, key partnerships with diverse collaborators will contribute to a better prepared and more resilient Puerto Rico.



FAILURE MECHANISM OF EDENVILLE DAM

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Purpose: Edenville Dam failed catastrophically on May 19th, 2020 (Figure1) after two days of unusually heavy precipitation near the town of Midland, MI (USA). Located about 16 km downstream of Edenville, Sanford dam failed subsequently due to overtopping in the following hours. The dam failures prompted the evacuation of over 10,000 residents during the COVID-19 pandemic, and together resulted in over $100M in damages. The slope instability that led to the breach of Edenville Dam occurred in the afternoon and was captured on video by a witness which was widely circulated in the national news media (Figure2). Although, Edenville dam was constructed before modern geotechnical engineering design practices and earth compaction quality control measures were routinely used in earth dam construction, the sudden slope instability failure of an earth dam that performed adequately for nearly a century surprised many geotechnical experts. Because the average age of dams in the USA is 57 years, and our country has thousands of earth dams of similar age (in Michigan alone 271 dams are over 100 years old), understanding the cause(s) of the slope failure at Edenville Dam failure is of vital importance.

Methods: The author led the ASCE reconnaissance team that investigated the causes of the failure of Edenville Dam and in this paper will present detailed observations he made at the site, key findings from the ASCE investigation, triaxial tests supporting a static liquefaction failure mechanism, and geomechanical numerical analyses he performed after the failure.

Results: Based on the evidence, two slope instability failure mechanisms have been considered likely for Edenville dam: a) Static Liquefaction: The embankment soils were predominantly of poorly graded sands (SP) that were not compacted and only pluviated in place; hence, had low dry densities which made them contractive. Loading from the rise in reservoir elevation resulted in static liquefaction of the dam's earth fill, causing the downstream slope to slide from the resulting loss of strength, in a similar manner to the 2019 failure of Brumadinho dam in Brazil. b) Slope instability: The rise in reservoir elevation resulted in increased pore water pressures and shear stresses that combined, permitted the development of a rotational slope failure. During the failure, the slide debris which was contractive in nature, expelled pore water in the form of water jets and flowed as it became liquefied along the toe of the dam.

Conclusions: Using the result of permeability tests, triaxial and direct shear laboratory tests, the author performed transient seepage analyses to estimate the rise in pore water pressures within the dam, as well as, geomechanical numerical analyses that indicate a static liquefaction failure mechanism comparable to the one recorded on video. Although static liquefaction is not a common failure mechanism, the Edenville Dam failure shows that old dams are vulnerable to such instabilities and thus should more often considered.

Fig. 1: Failed Edenville Dam.

Fig. 2: Water jets emanating from slide mass during failure.

FINITE VOLUME METHOD FOR COUPLED SURFACE-SUBSURFACE FLOWS WITH GEOTECHNICAL STABILITY EVALUATION

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Purpose: The majority of breaching of earthen embankments is triggered by overtopping flows or waves. These phenomena are usually simulated using the shallow-water equations complemented by the Exner equation to reproduce the progressive erosion of the embankment and the growth of the breached area. Such an approach usually neglects the effect of the degree of water saturation in the embankment as well as the flow through the embankment that can alter the stability of this structure by reducing the soil's mechanical strength. In the case of severe droughts preceding rainfalls, as observed during the summer 2022, desiccation cracks can appear and lead to preferential paths for the water to infiltrate the soil during subsequent rainfalls dangerously increasing the internal pore pressure.

Methods: Here we present a combined approach in which the flow through the embankment is solved using the Richards equation that is coupled to the system of shallow-water equations for the flow over the embankment. At the same time, the mechanical stability of the embankment is evaluated using the shear-strength reduction method. The groundwater flow is simulated by solving the 2D Richards equation on an unstructured triangular mesh with an implicit finite volume scheme, based on a direct gradient evaluation. The shallow-water equations are solved on a one-dimensional mesh using an explicit scheme with Roe's formulation for the fluxes. Finally, the shear strength reduction method is used on the same mesh as the one describing the groundwater flow considering the variation of pore pressure and saturation degree in space and time.

Results: Several tests were performed to demonstrate the ability of the proposed coupled solver to evaluate the influence of surface and subsurface flows on the mechanical stability of the embankment. In particular, the effects of initial soil's saturation degree and pore pressure fluctuation have been studied. The results point out that the initial saturation degree of the soil or the saturated hydraulic conductivity are of great importance on the time needed to reach failure while to dike is submitted to an overtopping flow.

Conclusions: A surface-subsurface flows solver coupled to the shear-strength reduction method is presented. This model allows to study the effects of pore pressure variation and overtopping flows on the stability of earthen embankment. This method can provide crucial information on the time needed to reach the full failure of the dike, a key-factor for the floods process assessment.

FLUME MODEL TEST ON GRANULAR MATERIALS FLOWING INTO A SMALL FILL DAM

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Purpose: The number of debris-flow incidents caused by landslides and hillside failures has increased. Small earth-fill dams that store water have occasionally suffered significant damage due to these disasters as many are located in valleys. (refer to Figure 1). Unlike debris barriers, earth-fill dams have a water storage function, and unlike large concrete dams, the embankment of small earth-fill dams can be directly affected by debris-flow. To understand the risk of debris-flow to these earth-fill dams, the mobility, generated wave, and impact pressure on the embankment must be known when the granular materials flowing down a slope, such as debris-flow, enter the water storage. In this study, a flume model test was conducted to investigate the basic characteristics of the first two factors.

Fig. 1: Failure of small earth-fill dam modified from 1)

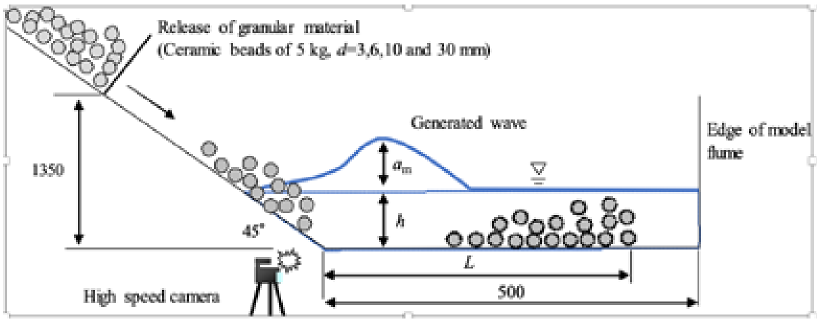

Fig. 2: Experimental method.

Methods: The model test flume was constructed from acrylic and consisted of two sections: a 2190 mm long slope inclined at 45°, and a 500 mm long horizontal water storage section. In each test, granular material was released from the 1350 mm height of the slope, and the flow length L of the granular material along the horizontal section and the wave amplitude am were measured (refer to Figure 2). The granular material was ceramic beads with diameters d = 3, 6, 10 and 30 mm. The water depth h was varied for each grain size.

Results: As shown in Figure 3, the am generated by the inflow of the granular material has an approximately linear relationship with the relative grain size d/h. From observations of the wave profile2), these waves were stable and did not break. When d/h exceeded 0.3, the wave broke quickly, resulting in a smaller amplitude. In addition, as shown in Figure 4, L increased with increasing d at any water depth. However, for d = 6 mm in Figure 4, L decreased by 27% when h = 40 mm was increased to 50 mm, whereas L decreased by only 6% when h = 50 mm was increased to 100 mm. The trend is the same in other case of d. The results suggest that a water depth zone exists where the mobility of the granular material is significantly reduced, and that this zone varies with the grain size.

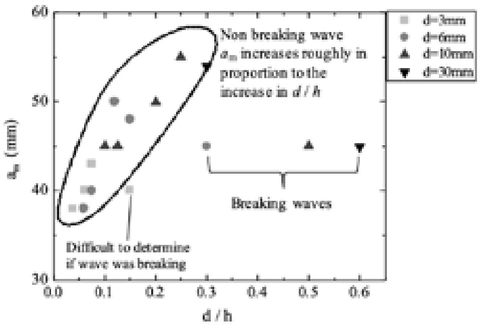

Fig. 3: Relationships between am and d/h in each d.

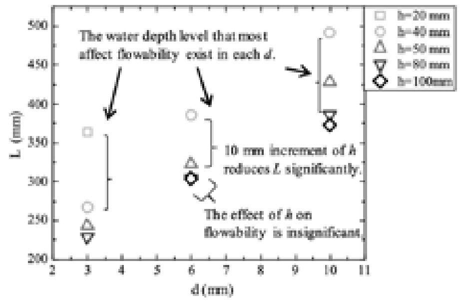

Fig. 4. Relationships between L and d in each h.

Conclusions: This model test provided insight into the relationship between the relative granular material size and wave amplitude, and into the water depth that influences the mobility when granular materials flowed into the water storage section. These findings are relevant for future large-scale model tests including an embankment model.

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MECHANISM STUDY OF SLIDING ZONE FORMATION AND FLUIDIZATION IN FINE GRAINED SOIL LAYERS OF A RAINFALL-INDUCED LANDSLIDE BASED ON RING SHEAR TEST

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Purpose: On 22 June 2022, a rainfall-induced landslide occurred in a terraced field in Guangxi Zhuang autonomous region, China. The landslide is designated as “Guilong landslide” thereafter. Under influence of the extreme and persistent rainfall, Guilong landslide developed multiple stages from cracking deformation to sliding runout, and finally transformed to flowlike movement. Fluidization was the most identifiable feature of this landslide, which was initiated in a soil layer in the source area and then extended to adjacent zone, eventually formed the sliding zone. The fluidization process of sliding zone was corresponded well with the multistage development process of landslide. The purpose of this paper is to clarify why fluidization occurred and sliding zone formed in a specific soil layer, and how this soil layer led to the multistage motion process of the Guilong landslide.

Methods: Laboratory tests for different soil samples collected during field investigation was conducted to classify the soils. X-ray diffraction (XRD) analysis was applied to investigate soil composition. As for the fluidization process and shear behavior of the soils under undrained condition, ring shear apparatus ICL-2 was used.

Results: XRD results revealed that a clay soil layer with higher plasticity and more complex composition transformed into sliding zone and continuously extended. This clay soil had higher content of clinochlore, muscovite, and kaolinite, and a small amount of anatase, while the soil above it was dominated by quartz and had relatively simple components. The ring shear tests of different soil were conducted under undrained condition. Results indicated that the soil layer which became sliding zone was easier to reach low shear strength under saturated state.

Conclusions: The fluidization characteristic of the Guilong landslide was closely related to a clay soil layer with high plasticity and complex mineral composition. Rainfall infiltration provided an undrained condition which led the soil in sliding zone to reach low shear strength. Fluidization started in sliding zone and caused the motion process of slide-flow of the Guilong landslide.

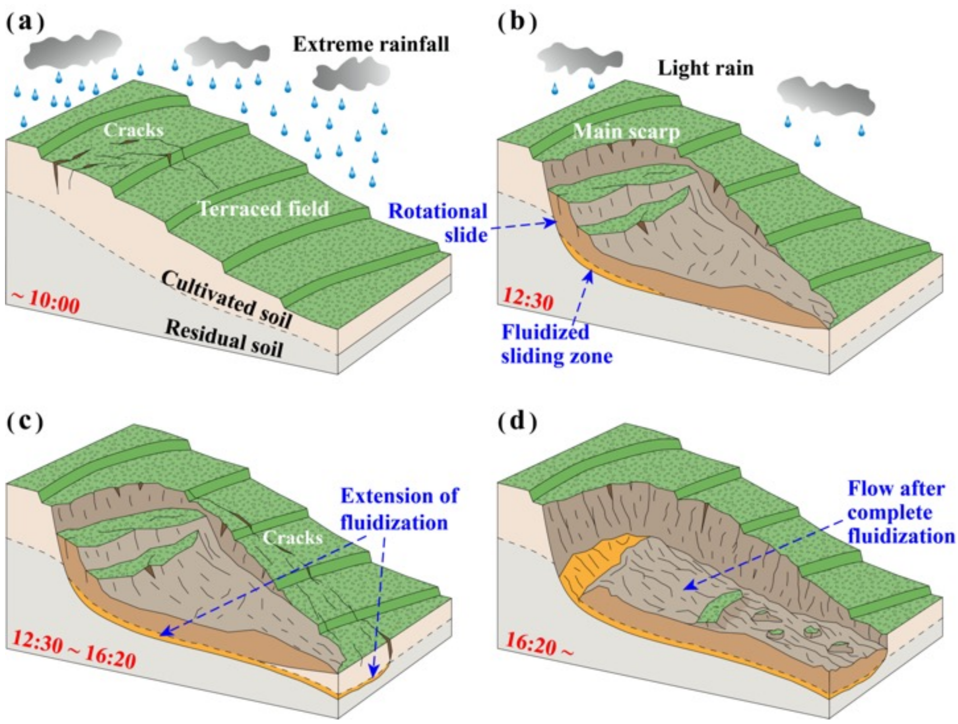

Fig. 1: Fluidization process of the Guilong landslide on 22 June 2022.

SESSION 4.3

WEAK POINTS IN LANDSLIDE SUSCEPTIBILITY MODELLING (part II)

FROM HILLSLOPES TO RIVERS, ACCOUNTING FOR THE ENTIRE LANDSLIDE SPECTRUM FOR INVENTORY, SUSCEPTIBILITY AND EXPOSURE EVALUATION

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Extreme rainfalls associated with tropical cyclones can have devastating impacts along the cyclone path. In mountainous regions, these rainfalls may trigger up to thousands of landslides, themselves feeding destructive debris-rich floods impacting downstream valleys sometimes over tens or hundreds of kilometres. Such compound events were observed in the mountains of eastern Zimbabwe alongside Cyclone Idai in March 2019. Hitting an area of high population vulnerability and exposure, this event had very-high human and geomorphologic impacts in the region. In the framework of the UNESCO project BE-RESILIENT Zimbabwe (funded by the World Bank and managed by UNOPS), we analysed the consequences of the landslides associated with this event in the Chimanimani and Chipinge districts of eastern Zimbabwe (~8000 km^2). Aiming at a rapid evaluation in a data-scarce region, we built on existing tools and open-access satellite remote sensing and GIS data to obtain an exhaustive inventory of the spatial extent of the impacted area, and ultimately an assessment of the population exposure in the region. We mapped over 14 000 (primarily shallow) landslides associated with this single event. Alongside a high population vulnerability, the extreme impacts of the landslides were associated with the extensive mobility - up to kilometre-long runout/deposition areas are found - of the landslides. To account for this, we distinguish three types of processes (zones) in our inventory, susceptibility, and exposure analyses: landslide source/depletion, landslide runout and debris-rich floods. This discrimination is key for apprehending the hazard imposed by landslides in the study area, and for properly evaluating the population exposure to this hazard. While this work aims primarily at guiding land use planning, mitigation, restoration, and prevention in the Chimanimani and Chipinge districts of eastern Zimbabwe, it also offers a case for the use of simple yet powerful approaches to assess the impacts of an extreme event and the exploitation of the astonishing amount of quality open-access data now available for every corner of the globe.

2023 NATIONAL SUSCEPTIBILITY MAP OF DEBRIS FLOWS IN NORWAY: NEW TOPOGRAPHICAL DATASET AND REVISED METHODOLOGY

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Purpose: Shallow landslides and debris flows are very common mass movement processes in Norway. They are important both within slope evolution and as they pose geohazards to society. Intense and/or prolonged precipitation events are the most common triggering mechanism, and predicted and recorded climate changes indicate that intense rain events will be more common in the future. National susceptibility maps are available for debris flows, snow avalanches, rock falls and fluvial floods. This susceptibility data is incorporated in national building regulations and trigger probability-based hazard evaluations for any infrastructure development. The presently valid debris flow susceptibility map was developed and released in 2014 and was based on old 10x10m resolution digital elevation data, utilised for starting point analysis and subsequent run-out modelling. As Lidar technology has revolutionised topographic data acquisition, the 2014 version needed to be updated. This study presents the results of a combined approach for renewed and modernised debris flow susceptibility modelling in Norway.

Methods: The new method builds on the framework developed for the previous version, updating it by i) using the new high-resolution digital elevation models, and ii) building and incorporating a new dataset of detailed manual point classification of previous debris flow activity in the landscape. Validation of the new susceptibility maps are done using detailed quaternary geological maps, satellite images, and fieldwork. The method is two-stepped, by first detecting potential starting points followed by runout modelling. For the discrimination of potential starting points an index approach was used for multivariate analysis, based on the topographic parameters slope and planar curvature, as well as water catchment areas (Rickenmann and Zimmermann, 1993). In this phase, two different process groups are considered: i) shallow landslides and open slope debris flows, ii) debris flows/debris floods in pre-existing channels which incorporate more water. All parameters are selected to 3 classes of landscape debris-flow sensitivity, based on the nation-wide mapping of previous activity. A runout model was then executed on all predicted starting point cells using Flow-R (Horton et al. 2013). For assessing runout distances, a probabilistic and energetic approach has been used (Holmgren, 1994; Horton et al., 2008) and results are manually validated to detailed quaternary maps.

Results and Conclusions: The preliminary analysis of the results shows a strong correspondence between modelled starting points and mapped debris flows. The general fit of the modelled runout length and area to the map is good. However, in some regions, the model shows some discrepancies, partly due to the runout being modelled using current topography, where the mapped deposits delineate a previous event. It may also be a consequence of a singular approach trying to fit a range of debris flow types in different geological settings without having the possibility to incorporate varying geology directly into the method. Overall, the new susceptibility map shows both higher topographical accuracy and better reflects the varying debris flow susceptibility of the Norwegian landscape than its 2014 predecessor.

EVALUATING THE POSTERIOR PREDICTIVE CAPABILITY OF LANDSLIDE SUSCEPTIBILITY MAPS; A CASE STUDY FROM KERALA (INDIA)

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Purpose: Landslide susceptibility maps are intended to serve as the basis for hazard and risk assessment, and for different applications, such as risk-informed land-use planning. These applications require accurate information as wrong decisions based on these maps may lead to increased exposure, loss of lives and infrastructure damage. However, relatively a few of the published methods indicate how the resulting landslide susceptibility maps should be used for these purposes, and how users should interpret the legend classes. Most of the published maps provide some sort of validation based on an inventory of landslides that occurred prior to the landslide susceptibility production date. Since the future landslide occurrences are unknown at the time of analysis, the model can only be tested against the past landslide occurrences. Many investigators attempt to create a pseudo-independent landslide inventory to test the model prediction performance by splitting the dataset over time and space. This is not in accordance with the overall objective of landslide susceptibility mapping, which aims at identifying the areas where landslides are most likely to occur in future, under possibly different triggering and controlling factors.

Methods: To address this, we evaluated three landslide susceptibility maps for an area in Kerala (India) that were generated using different approaches (physically-based modeling, statistical modeling and heuristic analysis). We generated new landslide inventories using the MsaU-Net deep learning model in combination with manual interpretation methods. We also designed a method to assess the predictive capability of the classified maps, based on comparisons in different scenarios, using Unique Conditions Units (UCUs) as a basis, in decision-making and spatial planning.

Results: The maps present overall similar percentages of susceptibility levels, but the classification differed substantially for individual units. This implies that evaluations should be conducted in various units (susceptibility classes, districts, UCUs) to present the degree to which the map provides reasonable accuracy at different scales. The maps did not demonstrate a strong relationship between landslide densities and susceptibility levels.

Conclusions: One significant limitation of the study was that only classified landslide susceptibility maps were available, preventing us from quantitatively evaluating these maps, using ROC curves. We conclude that there is an urgent need in the landslide susceptibility literature to focus more on the forward predictive capability and usability by end-users. Map producers should communicate with end-users on user requirements, and provide custom-made map legends that focus on specific decisions, as well as the associated uncertainties.

BEYOND MODEL PERFORMANCE: EXPLORING LIMITATIONS OF USING A SINGLE QUANTITATIVE PERFORMANCE MEASURE AS THE PRIMARY INDICATOR OF MODEL QUALITY

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Data-driven landslide susceptibility models (LSMs) have gained wide popularity in recent decades as a tool for assessing and mapping the potential for landslide occurrence in a given area. LSMs are commonly developed using statistical or machine-learning techniques that establish a relationship between spatial landslide occurrence (and non-occurrence) and variables describing “static” environmental conditions. The reliability of these models is usually assessed with performance metrics estimated in a hold-out or cross-validation framework. In this context, the Area Under the Receiver Operating Characteristic (AUROC) curve represents the most commonly used performance metric in the field. Literature suggests that important modelling decisions, such as the choice of input data or modelling algorithm, are frequently justified by an increased AUROC score, with a higher score presumably indicating a more reliable modelling result.

This contribution challenges such purely numeric practices based on our previous research experience. We provide examples of how inappropriate data sampling or the use of error-prone landslide inventories can lead to biased modelling results but, surprisingly, still achieve high model performance scores. It is shown that AUROC scores can artificially be enhanced by simply including a high portion of easy-to-classify terrain or by using data that describes and reproduces a bias inherent in the underlying landslide inventory data. It is also shown that models that closely describe post-failure topography, and not landslide susceptibility, can be associated with particularly high AUROC scores. Thus, this contribution highlights the need to consider aspects that quantitative performance measures cannot fully capture. We propose strategies for addressing several of the abovementioned issues. For instance, the propagation of inventory incompleteness into the final modelling results can be limited by avoiding predictors that directly relate to a suspected inventory error (i.e. bias-describing predictors) or by using mixed-effects models that “isolate” the effect of bias-describing predictors. In several cases, a too detailed description of post-failure topography can be counteracted by using alternative mapping units (e.g. slope units instead of pixels), by approximating pre-failure morphology or by simply resampling topographic data to a coarser resolution. Based on our examples, we stress the importance of geomorphic plausibility checks and highlight that the interpretation of one numeric measure alone may lead to misleading conclusions.

COMPARING OVER AND UNDER SAMPLING METHODS FOR LANDSLIDE SUSCEPTIBILITY ASSESSMENT USING MACHINE LEARNING MODELS: A CASE STUDY OF DJEBAHIA, NORTHERN ALGERIA

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University of Science And Technology Houari Boumediene, Bab Ezzouar, Algeria

Purpose: Landslide susceptibility modelling is a typical imbalanced classification problem, where the positive landslide points represent a small fraction of the data. However, most machine learning algorithms do not work very well with imbalanced datasets, and sampling is needed to properly implement the machine learning algorithms. Usually, a random or monitored under-sampling of an equal number of positive samples (landslide points) and negative samples (non-landslide points) is used to produce a balanced dataset. This study proposes the exploration of alternative under-sampling, over-sampling, and a combination of the two techniques based on the k-nearest neighbors approach to investigate their influence on machine learning models and to compare them with random and monitored under-sampling. The case study is the region of Djebahia, located in northern Algeria.

Methods: A dataset of 12 causal factors (slope, aspect, elevation, curvature, rainfall, NDVI, land use, distance to stream, distance to roads, and distance to fault, lithology, and TWI) and 115 landslides was used. Landslides were identified by points of landslide scarp, and all the factors were re-sampled to the 12.5-meter resolution of the digital elevation model. The methods employed in this study included NearMiss2 (NM2) (Mani and Zhang, 2003), Synthetic Minority Over-sampling Technique (SMOTE) (Chawla et al., 2002), and a combined over- and under-sampling approach using SMOTE and Edited Nearest Neighbors (SMOTE-ENN) (Wilson, 1972). These methods selected samples based on the distance between the specimens of the non-landslide class and those of the landslide class. Three machine learning models with different approaches are proposed, including Random Forest (RF), Support Vector Machine (SVM), and Multi-Layer Perceptron (MLP). The models were trained on 70% of the balanced samples, and then the performances of the models were assessed using each sampling method.

Results: Table 1, one of the results of this study, shows the area under the curve (AUC) of the receiver operating characteristic curves for each model and balancing sampling method. These results show a significant difference between the models and sampling strategies, with the SMOTE-ENN method showing the best performances for all the models and both test and overall sets, and SVM being the most performing model.

Table 1

	Models	RF	SVM	MLP
Monitored	AUC_test	0.935	0.928	0.882
	AUC_overall	0.979	0.976	0.893
Random	AUC_test	0.928	0.914	0.846
	AUC_overall	0.976	0.973	0.885
NM2	AUC_test	1.000	1.000	0.996
	AUC_overall	0.905	0.956	0.640
SMOTE	AUC_test	0.998	0.998	0.926
	AUC_overall	0.968	0.997	0.899
SMOTE-ENN	AUC_test	0.999	1.000	0.930
	AUC_overall	0.966	0.996	0.899

Conclusions: This study investigates under- and over-sampling techniques to assess how they affect machine learning models for landslide susceptibility modelling. The results showed that the NM2 method tends to overestimate global predictions, while the monitored and random under-sampling methods tend to underestimate them. Conversely, the SMOTE and SMOTE-ENN methods showed an improvement in both test and global predictions, with the disadvantage of increasing the calculation load. These findings highlight the potential of alternative balancing methods to improve the accuracy of landslide susceptibility models, thus contributing to the development of one of the weak points in this field.

INCLUDING CLIMATE AND URBAN CHANGE IN LANDSLIDE SUSCEPTIBILITY MAPS: SCALING-UP MECHANISTIC HILLSLOPE-SCALE MODELLING USING STOCHASTIC METHODS

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Climate change and unplanned urban expansion have the potential to increase the occurrence and impacts of rainfall-triggered landslides, especially in the humid tropics. Conventional regional and national landslide susceptibility mapping methods tend to not include these dynamic drivers, making them inadequate in a fast-changing world. Two challenges to be addressed are: including (future) rainfall infiltration, vegetation and housing on slope stability over large areas (> 100 km2) in a computationally efficient way; and accounting for uncertainty in these factors and in soil geotechnical properties and groundwater conditions, especially in data-scarce regions.

We report how Bozzolan et al. (2023) address these challenges for a case study in the Caribbean by using high performance computing and a newly developed mechanistic slope stability and hydrology model that includes both the urban and rainfall drivers (Bozzolan et al. 2020). First, we generate thousands of virtual hillslopes that represent many possible urban and climate scenarios as well as the uncertainty affecting soil properties and boundary conditions (e.g., initial water table). The mechanistic model is then run for each virtual hillslope and the simulated hillslope stability (available at https://data.bris.ac.uk/data/) is displayed in the form of landslide susceptibility maps ‘conditioned’ by a chosen rainfall event and urban scenario.

The susceptibility map built in this way and associated with a rainstorm event similar to the Hurricane Tomas (2010), correctly identifies ~70% of the landslides observed after that event. We then show that expanding informal housing (including deforestation) increases landslide susceptibility more (+20%) than intensified rainstorms due to climate change (+6%). However, when we consider the joint impact of these drivers, landslide occurrence in the region increases up to 40%, i.e., more than the sum of the two scenarios considered separately.

This work demonstrates the importance of representing both land cover and climate change as well as shows how mechanistic models can be used to quantify the relative impact of landslide drivers on slope stability under hypothetical future environmental conditions (e.g., how much deforestation could impact landslide rates compared to increasing unregulated urbanisation; or how much future rainfall has to intensify before a significant increase in landslide rates is observed). This information is often missing in data-scarce regions but can be crucial for supporting long-term landslide mitigation and climate adaptation policies.

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LANDSLIDE HAZARD ASSESSMENT IN THE COLOMBIAN ANDES

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Landslide hazard studies are valuable tools for land-use planning and regulation. They have been required at the local government level in Colombia since 1999. The first version of land-use plans, elaborated after 2000, implemented qualitative and subjective methodologies providing a shallow and general view of the real landslide hazard scenario. Actually, over 70% of local governments did not include a hazard map to constraint land-use development. According to this first experience, the Colombian Geological Survey (SGC) established technical guidelines for landslides and debris flow hazard assessment, which must be achieved by local governmental offices in charge of land-use planning. The methodologies proposed by the SGC imply high spatial resolution for urban areas and regional scales for rural areas, and a high number of environmental parameters that in most cases are not available, especially for small and remote regions. In this research, a selection of well known methodologies in literature was applied to several local government regions in the Colombian Andes. They were adapted and validated according to the specific conditions of each region and information available. The results show the uncertainty related to landslide hazard assessment, not only for regions where information is scarce, but high levels of uncertainty for regions where data is apparently enough, as well. Any landslide hazard zoning or mapping process involves high levels of uncertainty due to several limitations and potential sources of error. Particularly for the temporal component of hazard because of the lack of data sources with landslide frequency. For that reason, there is a fundamental step in landslide risk management related to informing inherent uncertainty involved in natural hazard modeling to decision makers.

SESSION 5.2

LANDSLIDES IN THE COLD REGIONS AND EXTREMES (part II)

LANDSLIDE SUSCEPTIBILITY ZONATION IN PERMAFROST REGIONS OF NORTHEAST CHINA CONSIDERING THE INFLUENCE OF PERMAFROST THAW

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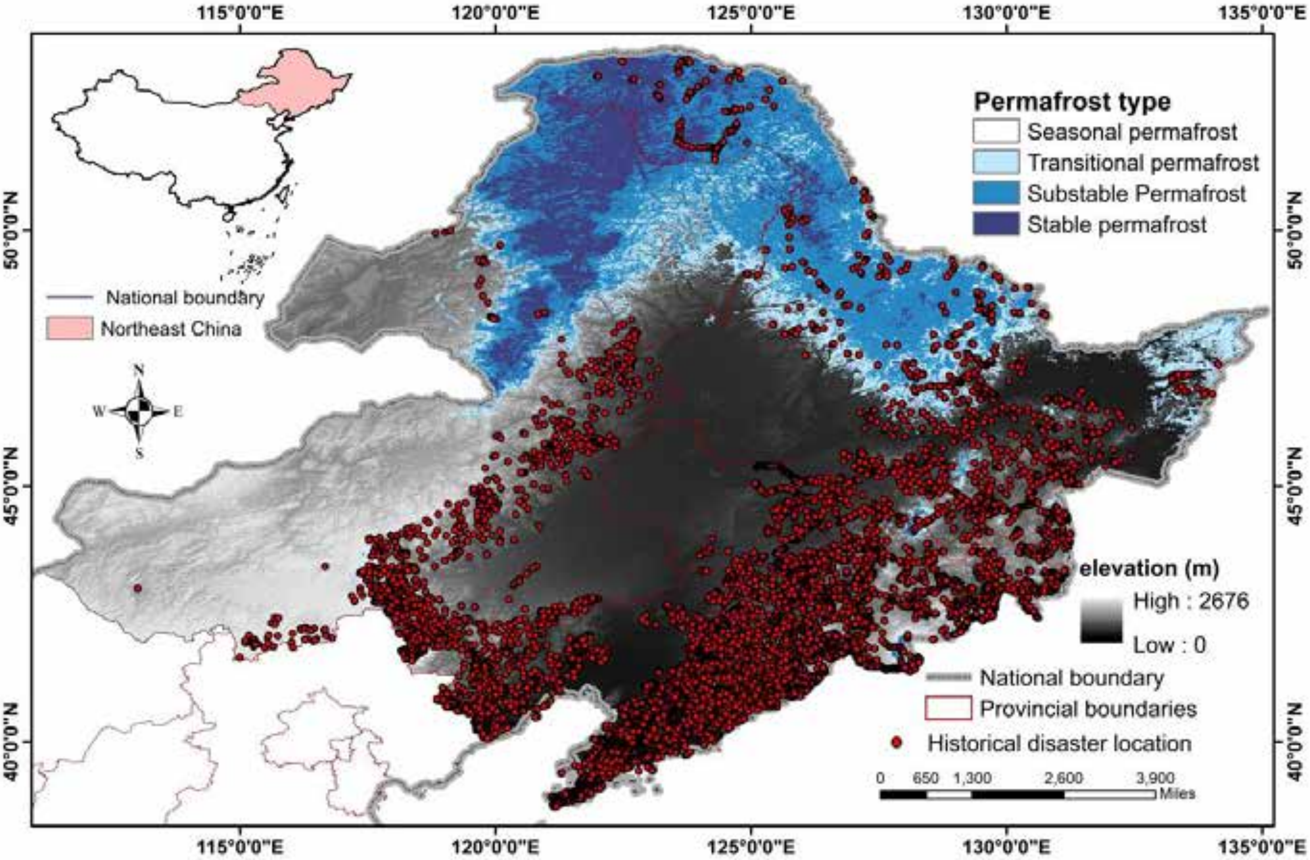
Purpose: Landslide risk assessment and landslide zoning have been effective ways of disaster mitigation and prevention advocated and promoted internationally. Long-term field investigations and studies have concluded that seasonal freeze-thaw and superposition of permafrost thaw and atmospheric precipitation are important exogenous factors for landslide movement in permafrost areas of Northeast China, and adding the freeze-thaw index as the influence and evaluation factor of landslide susceptibility in landslide zoning can achieve more accurate landslide susceptibility zoning in permafrost areas.

Methods: Remote sensing technology is a powerful technical means and method to obtain and update data information on ground temperature, moisture, and deformation. In this study, we take the permafrost zone in northeast China as the study area, based on a detailed landslide survey, cataloging, and remote sensing image interpretation, using data, images, and basic geological data, taking into account the permafrost degradation rate and other factors. Based on the detailed investigation and mapping of engineering geological conditions of the key sections, combined with the multifaceted images, meteorological data, and geological maps, the dynamic triggering factors of landslides, the stability and influence range of existing landslides, the frequency of landslides, and the annual probability of major triggering events, the risk of landslides is analyzed from the perspective of By correlation analysis and modeling of multiple influencing factors of landslides, the landslide inventory and landslide susceptibility risk analysis and mapping based on permafrost degradation index were carried out.



Results: The extraction and correlation statistical analysis and mapping of landslide susceptibility evaluation factors in the tundra zone of northeast China were completed, and landslide susceptibility zoning evaluation in Northeast China was realized by using different modeling methods.

Conclusions: Based on the landslide factor sensitivity analysis, the degradation degree of permafrost has an important influence on the occurrence of landslide disasters in permafrost areas that cannot be ignored. When engineering construction is carried out in the permafrost area, it is important to evaluate and predict the risk considering the permafrost phase and the changing trend in the construction plan site.

MASS WASTING ON PLANETARY BODIES - THE ROLE OF VOLATILES

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Purpose: Mass wasting is a common process on solid bodies in the solar system and takes many forms, including rockfalls, debris slides, debris flow and rock avalanches. Here, we focus on mass movements that might involve volatiles – substances (usually ices) which change to their gas phase readily under ambient atmospheric conditions for that body. The overall motivation of this work is to understand the morphological signature that volatiles impart to a mass movement and therefore be able to infer the presence of a volatile substance (and its quantity) on a planetary surface via studying the morphology of a mass movement. Volatile substances are usually found beneath the planet's surface and detecting them using subsurface sounding from remote sensing is challenging. Therefore, having an indirect method for detecting subsurface volatiles is of value. Such a method would use readily available image and topographic data from which mass wasting morphologies can be measured.

Methods: We use satellite images and topographic data from Mercury, Earth, the Moon, Mars, Vesta and Ceres to investigate the morphology of mass wasting features found on sloping terrain. Where possible we use topographic data, usually derived using stereo photogrammetry. On Earth and Mars the influence of volatiles on mass wasting processes is well-documented and on the Moon the landscapes are essentially volatile-free. Hence, we use these bodies as the end-members for comparing to Mercury, Vesta and Ceres, where the role of volatiles is not as well constrained.

Results: The main difference between volatile-driven mass flows on Earth and Mars compared to mass flows on the Moon is that those on the Moon do not extend beyond the angle of dynamic repose. We document mass movements on Mercury, Vesta and Ceres and find evidence that some of them are more consistent with volatile-enhanced mass movements on Earth and Mars than the dry counterparts on the Moon. These mass flows take the form of albedo streaks and/or lobate forms, often found on crater walls, but also on other types of sloping terrain.

Conclusions: Volatiles are an important driver of mass wasting processes on planetary surfaces and our study reveals that they may be active in mass wasting processes that modify sloping terrains on Mercury, Vesta and Ceres. Hence, volatile-driven mass wasting is important to take into account when considering the long term landscape evolution on these bodies.

COMBINING NUMERICAL AND MACHINE LEARNING MODELS FOR THE DETECTION OF LANDSLIDES INSIDE LUNAR CRATERS

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Purpose: Over time the Earth's surface is influenced by many external factors and as such landslides can be considered one of the most common destructive events shaping not only our planet but all terrestrial planets that are enveloped in a crust, including the Moon. Even though the predisposing and triggering factors can be different, lunar landslides can be easily categorized according to frameworks adopted on Earth, e.g., Varnes' classification. Lunar slump-like collapses are mainly occurring on the impact craters' walls deforming the natural bowl shape of craters from type "simple". Chebyshev's orthogonal polynomials have already been proven useful for interpolating and parametrizing craters' cross-section profiles, both affected and not from a landslide. However, a straightforward discrimination technique is still lacking to accurately distinguish between profiles containing landslides or not. As a simple linear threshold struggles to yield highly accurate results, this work lays the ground for the implementation of machine-learning approaches for precise classification of the crater cross-sections using Chebyshev's coefficients, i.e., an approach that can be ultimately used for compiling a lunar landslide inventory.

Methods: The proposed approach relies entirely on freely available data sources and software solutions. The main inputs used in this work are a lunar digital elevation model derived from Lunar Reconnaissance Orbiter Camera Wide Angle Camera, the locations and shapes of impact craters having a diameter between 10 and 20 km within the quadrant -90°E to 0° and -60°S to 60°N. 895 case study craters were selected and their cross-sections were extracted at each 10° using the craters' centre as a rotating point (Figure 1a). One-third of all elevation profiles were manually classified into distinctive classes and used as ground truth. The Chebyshev polynomials were used to interpolate and parametrize all profiles, and the derived coefficients of the ground-truth dataset were used for training and testing machine-learning models for classifying the profiles into distinctive classes.

Results: In total 6,660 elevation profiles were manually categorized into three classes "without landslides", "with landslides" and "distorted" (Figure 1b). The "distorted" class was defined as the distinct shapes of some elevation profiles did not fit in the characteristics of the other two classes. Of all trained models, the one depicting the highest classification accuracy was the one based on deep neural networks, able to reach during the testing phase Accuracy=0.90 and F1 score = 0.92/0.86/0.92, respectively for each crater's class. The resulting model was used for mapping the locations of craters exhibiting slumped walls in the selected study area.

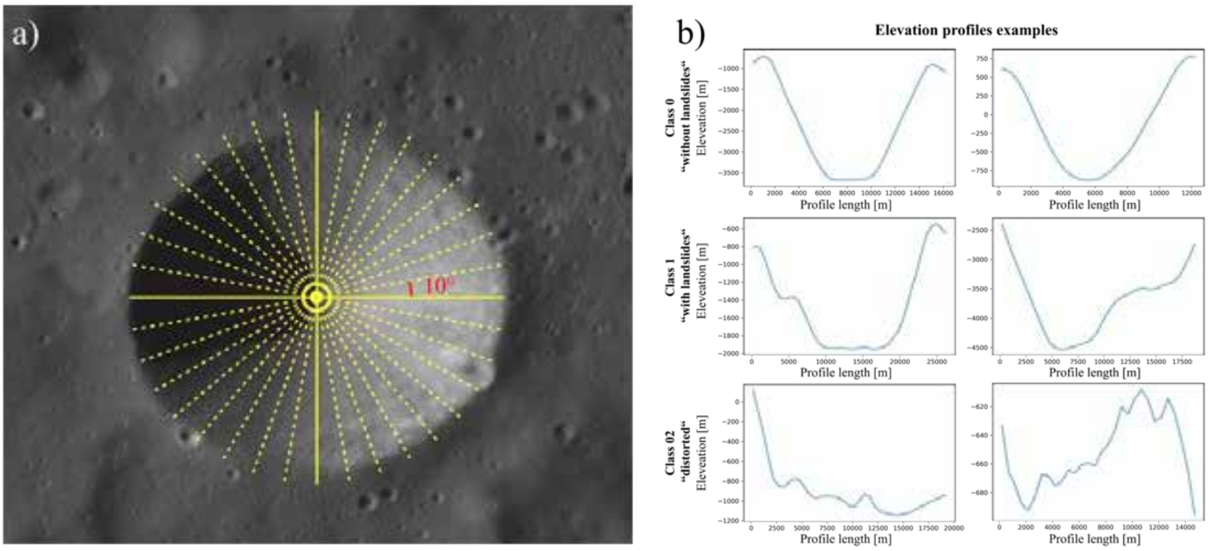

Fig. 1: a) example of crater cross-section extraction and b) example of the three distinct cross-section types.

Conclusions: The proposed approach combines numerical and machine learning models for fast and accurate classification of elevation profiles which can be directly used for mapping the locations of slumps in lunar craters. Even though it is not possible to map the entire spatial and volumetric extent of such mass slips, compiling such an inventory could potentially lead to new algorithms and studies for a better understanding of the phenomena on the Moon.

UNDERSTANDING SLOPE INSTABILITY MECHANISMS IN PERMAFROST ENVIRONMENTS

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Purpose: The rapid evolution of the landscape in the Arctic observed over many years is of concern from a climate perspective, but also regarding emerging natural hazards. Part of this evolution involves soil deformation, which, by redistributing soil and organic matter, impacts the soil carbon cycle, but also poses a threat to infrastructure and communities. The variety and complexity of the mechanisms controlling soil movement is a significant source of uncertainty in estimating current and future hazards, soil carbon storage and fluxes. A better understanding of the soil deformation triggers and kinematics will allow us to better understand their impact on climate change and improve the mitigation of the hazards.

Methods: In this study, soil deformations and their controls in an Arctic environment have been investigated using a dense, low-cost sensor network. Each sensor provided depth-resolved deformation and temperature measurements to depths up to 1.8 m (Wielandt et al., 2022). The sensor network was deployed at 59 locations across a 2 km2 watershed located on the Seward peninsula. Deformation and temperature were monitored at 15 min intervals from May 2022 to September 2022.

Results: During this period, the watershed experienced air temperatures exceeding 0°C and numerous rain events, leading to critical conditions for soil deformation. Displacements of a few millimeters to tens of centimeters were recorded to depths up to 1.8 m. These displacements showed different spatio-temporal patterns that vary as a function of the topographic position, the subsurface structure, and the thermal and hydrological states. While some locations showed a clear relationship between seasonal thaw depth and soil deformation, other locations remained stable. A detailed analysis of the data allowed us to highlight the different factors controlling the deformation (e.g. slope aspect, permafrost depth, soil temperature, bedrock depth, soil moisture, etc.).

Conclusion: Here, we investigate the impact of the different thermal-hydrological and topographical factors on the evolution of the morphology of an Arctic watershed. We show that the permafrost temperature has a major control on slope instabilities in these environments. By investigating the spatio-temporal dynamics, this study provides a better understanding of the mechanisms controlling hillslope deformation and their possible impact on the soil carbon distribution and the hazard they may represent. Also, this study allows us to move a step closer to the prediction of areas prone to slide in the context of global warming.

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MULTISTAGE EVOLUTION, A LONG PREHISTORY AND PERMAFROST DEGRADATION - REVISITING THE GIANT TSUNAMIGENIC 2000 AD PAATUUT LANDSLIDE IN GREENLAND

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Purpose: In November 2000, the c. 50*106 m3 Paatuut landslide in West Greenland triggered a tsunami with a runup of at least 45 m near the landslide impact. Although the landslide was examined by field teams after it happened, prior events and processes were never studied, and nothing is known of what caused the landslide.

Methods: To close this knowledge gap, we have analyzed field data along with satellite images and historical photos.

Results: We found that a landslide of similar magnitude occurred at the same slope in 1996. The traces of this landslide were obliterated by the subsequent 2000 landslide. The resulting tsunami of the 1996 landslide only had a runup of c. 15 m near the landslide impact. We applied tsunami modeling and interpretation of morphological field evidences to explore why the tsunami generated from similar volumes on the same slope could result in such different tsunami runups. Our analysis suggests that the 1996 landslide was a frozen debris avalanche. The landslide deposit draped an otherwise dry slope with permafrozen talus that quickly melted, producing a large wet volume that could be entrained in the 2000 landslide. The source material of the two landslides also differed in that the 1996 landslides was comprised exclusively of permafrozen talus while the 2000 landslide consisted partly of permafrozen talus and partly of brecciated/sheared previously failed bedrock of Paleogene volcanic rock. Analysis of aerial images from the decades leading up to the events shows that the 1996 landslide was likely triggered by a permafrost degradation landslide eroding the toe of the talus slope since the 1970s. The 1996 landslide then prepared the slope for the 2000 landslide. Furthermore, we see clear evidence of much older post glacial landslide activity on the slope that also constituted a static preconditioning factor for the landslides.

Conclusions: These landslides demonstrate the patchy record of large landslides in the Arctic along with the importance of landslide dynamics and entrained material in determining tsunamigenic potential. Above all it also demonstrates the sensitivity of these slopes to warming and permafrost degradation as has also been demonstrated by other recent nearby landslides (Svennevig et al., 2022, 2023).

Fig. 1: The 2000 AD Paatuut landslide a couple of days after the event. The 45 m runup of the tsunami is seen in the absence of snow along the coast. The mountain is 2 km high and the landslide source is in the centre of the image is 4 km inland. Photo: Christoffer Schander.

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MOVEMENT PROCESS, DYNAMIC CHARACTERISTICS AND ENGINEERING COUNTERMEASURES OF LANDSLIDES CAUSED BY PERMAFROST THAWING IN NORTHEASTERN CHINA—A CASE STUDY IN K178+550 LANDSLIDE OF BEIAN-HEIHE EXPRESSWAY

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Purpose: With global warming, the permafrost in Northeast China is rapidly degradation, resulting in more and more unstable soil slopes. Engineering geological problems such as mountain landslides caused by thawing of frozen soil seriously affect the construction, maintenance, and operation safety of highways in permafrost regions. Therefore, it is necessary to conduct research on the sliding mechanism, movement characteristics, dynamic transformation, and support treatment of landslides in permafrost regions.

Methods: Bei'an-Heihe Expressway is located at the southern boundary of the Eurasian permafrost region and intersects the Lesser Kinggan Mountains in Sunwu County, China. The thawing of the permafrost has caused a large number of landslides, forming many mountain landslide groups centered on permafrost islands, seriously endangering the roadbed stability and operational safety of the Beihei Expressway. Through field investigation, engineering geological drilling, geophysical exploration, on-site long-term deformation monitoring, and monitoring data analysis of underground pore water pressure changes, the sliding mechanism, movement process, and dynamic transformation characteristics of K178+530 landslide were studied. At the same time, a two-dimensional model was established using finite element numerical analysis methods to simulate the sliding characteristics of the landslide.

Results: The Movement mode of the landslide is low angle seasonal creep. In the initial stage of landslide, the sliding force comes from the superposition of thawing of permafrost and atmospheric precipitation, which is characterized by the movement of the trailing edge pushing the leading edge sliding and accumulating loose material at the leading edge; After the trailing edge permafrost is completely thawed, the leading edge slides faster than the trailing edge, and the leading edge pulls the trailing edge to continue sliding. In the study of landslide sliding characteristics, the landslide is unstable under the natural state, and the trailing edge of the landslide has invaded the widened subgrade range. Adopting the widened subgrade method will cause the landslide to continue sliding and affect the overall safety of the subgrade. It is suggested and accepted that the plan of using bridge instead of widening fill roadbed, on the one hand, reduces the impact of trailing edge filling on landslide movement, and on the other hand, the bored pile of the bridge has supporting effect on the old roadbed on the non-widened side. This scheme not only improves the overall stability of the subgrade at the trailing edge of the landslide, but also effectively solves the problem of smooth traffic on the highway, greatly reducing the cost of later maintenance, and the highway has been in good condition since it was opened 10 years ago.

Conclusion: Through the systematic study on the landslides caused by thawing of permafrost in Northeast China, the new understanding of the movement process, dynamic characteristics and transformation law of the landslides, and the engineering countermeasures are obtained, the results of research and practice are of great scientific and practical significance.

SESSION 4.6

LANDSLIDES IN URBAN ENVIRONMENTS (part II)

RAIN-TRIGGERED LANDSLIDES IN URBAN CONTEXTS OF COASTAL SOUTH-CENTRAL CHILE

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Purpose: Chile is a country exposed to multi-hazards. Records show that many landslide events with fatal consequences have occurred in the last few decades, with heavy rainfall identified as the main triggering factor. Chile's south-central area (35°S–38°S) is particularly affected because the interaction of multiple factors that condition the occurrence of landslides, such as land cover, topography, geology, and wildfires, among others. Within this region, the Metropolitan Area of Concepción (36°30'S–37°30'S), epitomizes the combination of conditions favoring occurrence of slides, flows and falls caused by heavy rains. Thus, mapping hazardous areas becomes necessary to better planning. Despite the zoning of these hazards is integrated into a planning instrument called Communal Regulatory Plan, there is no standardized methodology for zoning landslides in Chile, precluding interoperability among offices tasked with planning and response to these events. For instance, while some of the current databases offer few details about individual events, most of them are recorded as discrete coordinates, where volume transported, or affected areas are rarely indicated. These data are fundamental for urban planning to be inputted in risk maps. Thus, the aim of this study is to develop a standardized landslide inventory to understand patterns of the conditioning factors that causes a higher probability of occurrence and to establish triggering rainfall thresholds.

Methods: To achieve this objective, a detailed landslide inventory is being developed, delimiting areas of scarp and deposition, geological unit in which they occurred, associated anthropogenic activity, among other parameters, expanding the catalog from the Chilean Geological Survey with: (a) historical data from local press, reports from municipalities; (b) interpretation of imagery such as medium and high resolution available from Google Earth Pro, orthophotos and high resolution LiDAR digital elevation models with vegetation filtered-out; and (c) field characterization of recent deposits with UAVs.

Results: Preliminary results show that 53% of the landslides correspond to slides, 22% flows, 13% falls, 2% complex movements, 1% lateral spreading and 9% undifferentiated movements. 86% of recorded landslides were triggered by heavy rains. One of the examples of rotational slides is in the town of Penco, where more than 12,000 cubic meters of clayey fill were displaced. This slide has been active since 2013, since the transformation from a forested area to an urban zone, as a housing solution for people affected by the Maule earthquake of February 27, 2010 (Mw = 8.8). Despite having been a "solution", this sector has been affected by both wildfires and landslides after its development, which presents a clear example of the multi-hazards of south-central Chile.

Conclusions: The compilation from various sources to generate the Landslide Inventory has made it possible to clarify landslide patterns in the coastal areas of south-central Chile. Although the annual rainy periods span from May to October, the greatest occurrence of landslides is concentrated in the months of June, July, and August. However, results also show that intense rainfall accumulated in September and October should not be underrated, since then the soil is mostly saturated, making it more prone to slide likewise.

THE WATER LEVEL FLUCTUATION EFFECT IN LANDSLIDE STABILITY AND TRIGGERING IN DAMS, SUSCEPTIBILITY MAPPING: A CASE STUDY IN BENI HAROUN DAM (MILA, ALGERIA)

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Purpose: In the Mila region, the Beni Haroun dam is the largest in Algeria, with a 960 million m3 storage capacity. The reservoir is essentially formed by the elongation of the two Rummel and Ennja wadis, which develop in the Constantinois Neogene basin, characterized by clay and marl soils sensitive to gravity movements. The landslides inventory carried out shows that this phenomenon is very common in the region in particular, the slopes that delimit the Beni Haroun dam, which are affected by different sizes of landslides located at different altitudes. This variation in altitude location is probably due to the water level fluctuation in the dam during the year. This study examines the water fluctuation level on the slope stability in Beni Haroun dam.

Methods: For this purpose, a number of searches for breaking surfaces and finite element analyses were conducted on full-scale geological-geotechnical cross-sections. The software Talren V4 and Plaxis 2D were used which are based on the two-dimensional Limit Equilibrium Method (LEM) and the Finite Element Method (FEM), respectively. The geological formations were described by a non-linear hardening soil model, an advanced elastoplastic stress-strain constitutive soil model. According to the lithological nature of the slopes that delimit the dam, five representative cross-sections were studied and subjected to different levels of water fluctuation in the dam. For a better result, ninety numerical analyses were executed between LEM and FEM methods.

Results: According to numerical analysis results, the water fluctuation level and the slope angle have a very significant effect on the safety factor (FS) of the slope subjected to water fluctuation level. It was also noticed that the water fluctuation level and a steep slope have a greater impact on the slope stability than the water fluctuation level and low slope.

Conclusions: From the results, the clayey slopes characterized by steep slopes have more effect on the safety factor (FS) and the landslide triggering. Finally, the results will make it possible to determine the different classes susceptible to landslides after analyzing the relation between safety factors, slope sections, and water fluctuation levels in the dam and to develop a landslide susceptibility map.

IMPACT OF GREENING IRRIGATION ON POTENTIAL SLOPE INSTABILITY SURROUNDING URBAN AREAS: A CASE STUDY ON A MUDSTONE LANDSLIDE IN SEPTEMBER 2022, QINGHAI, CHINA

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Purpose: On 15 September 2022, a landslide occurred in Jiujiawan village, Xining city, Qinghai province, China (N 36°41′45″, E 101°47′05″) (Figure 1). Although there was no rainfall within 10 days before the event, the landslide suddenly occurred at 17:25 (UTC+8) and interrupted the Lanzhou-Xinjiang high-speed railway, a vital passenger transport line in western China, and destroyed several houses, plants and a hilly road was buried.

Fig. 1: Location and panoramic photograph of the Jiujiawan landslide.

Since no earthquake and engineering activity occurred surrounding the landslide site, the long-term greening project on the slope was estimated to be one of the potential triggering factors. According to statistics, Xining added 500 km2 of greening area within 2022 to alleviating the arid environment on the Loess Plateau. However, the greening irrigation potentially affected the slope stability in such area with mudstone bedrock.

Methods: A field investigation was carried out on 15 September to study the geological conditions and landslide characteristics. Soil hardness test and rock mass rebound were performed to study the strength of rock stratum. After the in-situ tests, laboratory experiments were carried out to figure out the influence of infiltration on the degradation processes of the rock mass. Besides, remote sensing image analysis was used to analyze the surface deformation induced by the groundwater.

Results: The bedrock in landslide site consists of Neogene sandy mudstone interbedded with gypsum rock. The rock mass should be classified as soft rock because the uniaxial saturated compressive strength was lower than 20 MPa. The mudstone near the groundwater outlet has been disintegrate into soil with a hardness index of 1.95 MPa. Both mudstone layer and gypsum rock layer have water-softening characteristic. Due to the irrigation of slope greening, the compressive strength and elastic modulus of stratum gradually decrease, leading to the long-term deformation of the original slope.

Conclusions: With the continuous progress of urbanization, people require a higher level of living environment in urban areas. More and more greening project will be carried out in the near future. Therefore, attention should be paid to the influence of greening irrigation on the slope stability, especially in the soft rock or water-sensitive rock region. While improving the environmental the potential landslide risk near the urban areas should be assessed carefully.

ASSESSING THE IMPACT OF DEFORESTATION AND FORESTRY INDUSTRY ON LANDSLIDE PROBABILTY IN CHILE'S WILDLAND-URBAN INTERFACE: A CASE STUDY OF PALOMARES BASIN IN THE METROPOLITAN AREA OF CONCEPCIÓN

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Purpose: Chile faces diverse and mixed hazards due to its unique combination of geographic, geological, climatic, and anthropic features. In the Metropolitan Area of Concepción, rainfall-induced landslides are one of the most recurrent and destructive hazards, causing the death of at least 17 people since 1980, and incurring high monetary losses for material goods and infrastructure. The Palomares basin, located at Concepción outer limit, is an urbanization surrounded by plantation-covered hills, which constitutes a wildland-urban interface (WUI; forest-land and urban area of contact), combining both wildfire risk (e.g. 2017 and 2023 wildfires), and landslides, due to loss of vegetation cover and subsequent increase of erosion, portraying a new type of territorial problem and our aim: Effects of deforestation and forestry industry in landslide generation inside the WUI. We chose this area as it embraces a common, distinctive, and not well-considered scenario observed in the region, with presence of natural features: (1) deep, well-formed soils from regoliths of highly weathered granitic mountains, (2) steep slopes, (3) high-intensity rainfall, and social factors: (1) occupation of hill-related marginal areas in dangerous zones because of socio-economic segregation, (2) insufficient territorial planning, (3) anthropic augmentation of landslide-conditioning factors related to deforestation. We suggest that decrease of mechanical soil properties and loss of root cohesion due to consecutive harvest cycles and wildfires are significant factors that increases landslide probability and must be considered in the assessment and planification of urban zones and WUI, where combination of multi-factorial socio-natural features generates this type of high-exposure socio-natural risk.

Methods: Pre and post-deforestation scenarios were simulated using the STEP-TRAMM software. Input data was a 2019 rainfall event, soil depth (m), elevation (0.2 m2 and 12.52 pixels for a single slope and the whole basin, respectively), soil textural class, friction angle (°), landslide inventory (fieldwork and tele-detection) initial soil saturation (ISS), root strength (Pa), soil cohesion (Pa) and presence/absence of vegetation cover (tele-detection of pre-post deforestation scenarios. The software quantifies spatio-temporal landslide probability and dimensions by considering the mechanical loss/gain of soil cohesion given by tree roots. Scenarios are then validated with the landslide inventory and compared to quantify the effects of deforestation.

Results: Landslides occurrence probability increases under deforestation conditions, with post-deforestation scenario showing up to 3 and 5 times more generated landslides and displaced material (m3), respectively. For both single-slope and basin scale, more than 65% of simulated landslides concur with the landslide and instability inventory identified from the 2019 precipitation event. The simulations at a single-slope scale suggested that ISS levels between 0.4 and 0.65 were the best fit for space, temporal, and volumetric landslide generation, with a small time-gap between the simulated and real scenario. On a whole basin scale, simulations were interpreted as landslide-triggering areas, where real landslides were registered within these zones.

Conclusions: Under same precipitation event, the probability of landslides occurrence increases under deforestation conditions, increasing the risk of population that is exposed because of the combination of insufficient urban planning, invasive forestry practices and the inherent susceptibility of inhabited slopes to landslides.

SMOOTHED PARTICLE HYDRODYNAMICS BASED NUMERICAL MODELLING OF INTERNAL EROSION-INDUCED SUBSIDENCE AND CONSEQUENT LANDSLIDES IN HILLY REGIONS

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Purpose: Internal erosion is a phenomenon in which water flows through a soil structure due to specific critical hydraulic gradient and gradually removes fine soil particles or other materials, leaving behind larger particles or voids that cause instability and loss of strength. This process can result in formation of underground cavities, eventually leading to subsidence or collapse of the ground surface. Land subsidence usually occurs due to surface settlement in an aquifer due to the void ratio change or densification of unconsolidated sedimentary deposits or due to internal erosion characterized as suffusion and suffosion. The consequent ground subsidence rate depends on the complex and coupled mechanism within withdrawal of ground water resources, consolidation of sedimentary deposits, and internal erosion due to water flow. Hilly regions are severely prone to the ground subsidence due to apparent environmental, geological, and social setting particularly in areas with high rates of groundwater extraction, unstable geology, and heavy rainfall. In the hilly regions, the subsidence can occur over a large area, leading to large depressions and consequent landslides. Moreover, if the region happens to be seismically active for example the Joshimath region in Indian Himalayas, where land subsidence is taking place at an alarming rate, the instability is going to increase significantly making the problem even more complex. The process can have significant environmental and economic impacts, as it can lead to land loss and infrastructure damage, including buildings, roads, and pipelines. Understanding the mechanisms of internal erosion especially under the strong events of earthquakes and implementing appropriate measures to prevent and/or mitigate the consequences is critical to ensure the safety and stability of the associated built environment. The 3D consolidation, non-uniform water pumping, suffosion, and suffusion associated with land subsidence in hilly region makes it multiscale problem which needs to be properly modelled numerically to get an in-depth insight into the problem. Due to delicacies and complexities involved in the hyper gravity (centrifuge) testing and apparent limitations of 1g experimentation, there is a pressing need to develop and calibrate a sophisticated coupled numerical tool to better capture the mechanics of ground subsidence and assess the consequent effects on the built environment.

Methods: In this study a multiscale numerical tool is developed using Smoothed Particle Hydrodynamics (SPH) to investigate the phenomenon of internal erosion-induced ground subsidence and the physics involved under dynamic effects. SPH is a truly mesh-free, particle-based Lagrangian method, which tracks individual particles' movement through the simulation domain.

Results: Using this approach, critical issues related to subsidence and consequent landslides such as physics-based modelling of land subsidence (m), estimation of site-specific critical state (hydraulic gradient) owing to initiation of internal erosion, failure surface and runout distance (m), flow velocity (m/s) and inundation depth (m) of landslides is modelled.

Conclusions: It is observed that SPH can effectively capture the physical internal erosion of soil particles along with the resulting subsidence as well as the run-out generated post failure under the effect of dynamic action.

ADAPTATION OF THE VULNERABILITY ASSESSMENT ON GEOLOGICALLY COMPLEX COAST

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Purpose: The complex geologic fabric and geomorphology require adaptation of the existing methodology and detailed approach to coastal vulnerability analysis. Problems of marine erosion, coastal recession and slope instabilities are known along many coastal sections in the northeastern Adriatic. The coastal area around Stara Baška settlement (Krk Island, Croatia) is in a vulnerable geodynamic equilibrium. The major problems in this area are the erosion of the coastline and its local instabilities (Figure 1), which are influenced by geomorphological processes, sea level fluctuation, and exposure to wave attack. The unplanned expansion of settlements and intensive construction of tourist facilities, as well as the lack of an appropriate water drainage system, have greatly influenced the vulnerability of this area. Depending on the local geological conditions, the coastal cliffs are prone to collapse, so boulders are often found on the beaches, posing a risk to tourist camps.

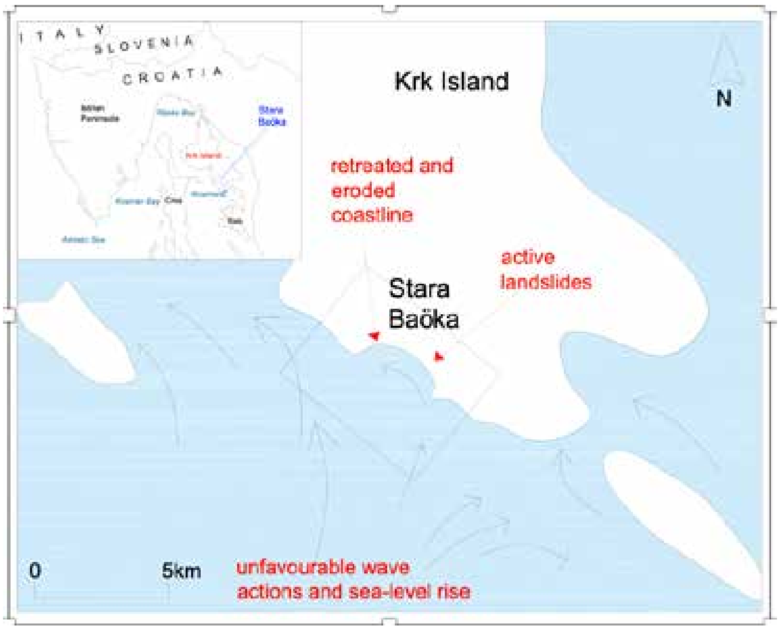

Fig. 1: Location of the study area around Stara Baška on Krk Island and the dominant geohazards in the investigated area.

Methods: The coastal vulnerability analysis in this study is based on existing data and a field survey of a narrow coastal area approximately 8 km long, considering five parameters: geologic setting, coastal slope, beach width, significant wave height, and land use. Index-based approaches express coastal vulnerability using a one-dimensional originally proposed CVI index. The method is based on segmenting the coastline and assigning vulnerability values to each coastal segment. The calculation is done for every 5 m of the approximately 2 km long coastline. The resulting errors in the application of the original method, verified in practice, led the authors to adopt the method for the representation of complex conditions. Factors considered in the analysis were ranked from very low to very high. Coastal vulnerability (CVI) index were determined on the basis of field investigations and statistical parameters.

Results: The paper presents the results of the analysis according to the existing methodology, and differences when applying the changes proposed in the new approach. The results of the complex novel vulnerability assessment show better agreement when using terrestrial and aerial photogrammetry for verification. These differences are localized and within one vulnerability index class. Greatest differences are at the most and least vulnerable coastal sections.

Conclusions: Two CVI analysis approaches showed no significant differences on wider coastal section, but locally there are significant differences. If geologic fabric is not recognized as the most important parameter for CVI analysis, CVI is underestimated in the most vulnerable coastal section and overestimated in the least vulnerable. The presented method was used to identify the most vulnerable coastal sections, which provides the basis for future coastal management and land use planning. Predicted sea level rise and increase of the rainfall intensity due to climate change, will further increase costal vulnerability in this area. The analysis has confirmed the necessity of the vulnerability analysis in the process of land use or urban planning, as well as the need to establish the coastal monitoring in the urbanized zone of the Stara Baška settlement where landslides may occur.

UNVEILING THE RELIABILITY OF MULTI-SCALE LANDSLIDE SUSCEPTIBILITY MAPS AND MAXIMIZING THEIR POTENTIAL THROUGH FUSION

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Purpose: The expansion of urban areas demands correct and sustainable urban planning, and LSZ studies can provide valuable products for correct land use planning and risk analysis. The purpose of this study is to assess the reliability and potential of small- to medium-scale landslide susceptibility zonation (LSZ) in urban areas, where regulatory plans with detailed geohazard-related data are often lacking. The study also aims to evaluate whether merging low-resolution LSZ can lead to a significant increase in accuracy and reliability of the original maps, making them more applicable for advisory purposes.

Methods: The study employs geospatial Machine Learning (ML) to generate a predictive LS map at an urban scale for the Municipality of Rome. ML algorithms are used to identify relationships between landslide initiation points (LIP) and to train and cross-validate several models, with the best-performing one selected and its hyperparameters refined to improve predictions. The obtained predictions are then compared with open-source regional, national, European, and global scale LS products to quantify their performance and overall reliability. Event-based test samples from 67 rainfall-triggered landslides of January 31, 2014 are used to determine the capability of multiscale LS maps to correctly detect landslide occurrences. Statistical and spatial analysis are used to assess the accuracy of each collected LSZ and to merge the maps for improved landslide susceptibility prediction.

Results: The results of the study show that the predictive LS map generated by the ML algorithms reaches 90% accuracy on the test set. The comparison of the obtained predictions with other LS products demonstrates the strengths and weaknesses of the LSZ. The spatialized accuracy assessment reveals true/false positives and negatives in the space and reports the overall confusion matrix and metric scores, with F1 scores used as a weighting parameter for merging the LS maps. A cumulative and pairwise fusion approach was tested, revealing an increased ability of multiscale LSZ to detect occurred landslides while maintaining precision.

Conclusions: The conclusion of the study is that the fusion of national, European, and global maps can significantly help in better predicting landslide occurrences in urban areas, especially when more detailed studies are lacking. The use of geospatial ML algorithms and data fusion criteria can lead to a significant increase in the accuracy and reliability of small-scale maps, making them more applicable for informing or advising land use planning. The fusion of national, European, and global maps can also help in better predicting landslide occurrences in urban areas, highlighting the importance of integrating multiple scales in LS studies.

16:00-17:00 | HALL 2

CLOSING CEREMONY

Chairs: **Snježana Mihalić Arbanas** - *Chair ICL Network Committee* and **Faisal Fathani** - *ICL Vice-President*

16:00 Bestow of WLF6 PhD Award
for the best oral presentation held by a PhD student

16:10 Speech by the WLF6 Forum Chair and Certificates to new ICL Members
Nicola Casagli - *ICL President and Chair of the 6th WLF*

16:30 Speech by the new ICL President and Introduction of the new ICL officers
Željko Arbanas - *ICL Incoming President*

16:50 Welcome Address to WLF7
Jia-Jyu Dong and **Chih-Chung Chung** - *Chair and Organizer of the 7th World Landslide Forum*

E-POSTER SESSION

THEME1

KYOTO LANDSLIDE COMMITMENT FOR SUSTAINABLE DEVELOPMENT

P1.1
DEVELOPMENT OF LANDSLIDE SUSCEPTIBILITY MAP FOR RAIN-INDUCED LANDSLIDE BY INTRODUSING THE FACTOR OF SAFETY MODEL IN SRI LANKA

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Purpose: The landslide susceptibility map projects were started in 1989 in Sri Lanka. This area's most important natural catastrophe is landslides brought on by heavy rain during the monsoon and inter-monsoon seasons (JAYATHISSA et al., 2019). Due to the growth of human settlements into increasingly vulnerable hill slopes and the rising demand for land for construction activities, this has grown significantly in the current situation. Mainly six causative factors as Geology, Slope, Hydrological factors, Soil thickness, land use patterns, and Landform have been considered to develop such a landslide susceptibility map in Sri Lanka. The development of Sri Lanka's landslide susceptibility map, however, did not take into account the mechanical and hydraulic properties of the soil. The primary goal of this study is to develop a spatial distribution of safety factor models for the specific basin in Sri Lankan regions that are extremely prone to landslides.

Methods: The United States Geological Society's (USGS) Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Model (TRIGRS) factor of safety model will be introduced, and it will be used to create a factor of safety models for various soil initial conditions and rainfall patterns. Using historical landslide incidents, the factor of safety model was validated. The case study location is located in Sri Lanka's hill country, which is prone to landslides. In a chosen catchment, four separate landslides occurred, and field research work is currently ongoing to determine the kind of landslide and establish input parameters for the TRIGRS model. Finding accurate rain-induced landslide initiation zones is the study's ultimate objective. Do a risk zone assessment for the debris flow following the landslide as well.

The evaluation of the soil's unsaturated behavior was done by plotting the soil water characteristic curves. Other mechanical qualities of the soil will also be determined through the laboratory test.

Results: The developed factor of safety map showed several visual similarities between the deterministic factor of safety model related to slope instabilities and the landslide hazard zonation projected by NBRO's technique. But still, the factor of safety model's predictions for historical landslides revealed extremely precise landslide initiation regions.

Conclusions: The factor of safety maps, which were created using deterministic techniques demonstrated the quantitative stability of a site while taking into consideration the most significant variables that have a direct impact on the stability of the slope. Future study findings will aid in the enhancement of Sri Lanka's current landslide hazard zonation map.

References

1. Jayathissa G, Schröder D, Balke K-D, Fecker E. Landslide Hazard Zonation in Sri Lanka: An Assessment of Manual and GIS Based Automated Procedure in Preparation of Geology Weight Map. International Journal of Erosion Control Engineering 2019; 11(4): 116–123. https://doi.org/10.13101/ijece.11.116

P1.2

OBSERVATION OF SLOPE DEFORMATION AROUND THE LANDSLIDE IN ATHWELTHOTA IN SRI LANKA

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Purpose: Sri Lanka is located in the tropical monsoon region, and heavy rain occurs repeatedly during the rainy season. Heavy rain causes many landslides in mountainous areas. It is important to clarify the mechanism of landslide triggered by heavy rain in order to effectively mitigate the damage. Since the occurrence of landslides is affected by local characteristics such as soil property and rainfall characteristics, it is necessary to clarify them of the landslides. Therefore, field observations were conducted on unstable slopes near the previous landslide in order to clarify the mechanism of the first stage of landslide occurrence in mid-mountain area of Sri Lanka. In SATREPS RRLL project in Sri Lanka, characteristics of slope displacement in unstable slope is investigated by the relationships between rainfall and ground inclinometer.

Methods: This study is conducted in the Athwelthota site in Western Province of Sri Lanka. The landslide was caused by heavy rain in May 2017. It was approximately 400 m length and 50 m wideness. The slope around the landslide is steep with a slope gradient of approximately 30 degrees. And it was unstable due to steps and cracks that were thought to be caused by past displacement. Therefore, we installed a ground inclinometer on the right slope of the landslide site and began displacement observations. We also conducted meteorological observations to investigate the relationship between rainfall and slope movement. The ground inclinometers were installed at 10 points in target slope.

Results: Although the data is not yet satisfactory due to the short observation period, the following findings have been made so far. Rainfall is characterized by a rainy season with continuous rainfall and a period of relatively infrequent rainfall. During periods of low rainfall, rainfall intensity is high but duration is short. Small steps related the small past slope failure were identified on the slopes. And even on slopes with no cracks, it was found that there was an accumulation of small displacements. However, the magnitude of the displacement was small enough to be detected by the inclinometer sensor. In some areas, displacement showed creep-like behavior independent of rainfall, while in other areas, the displacement showed complex behavior such as repeated increases during no rain periods.

Conclusions: At the study area, no major displacement was observed no the steep slope around the landslide area, but cumulative microdisplacemet was found to be present. The movement was complex. The soil layer was relatively thin on the slopes, and groundwater seepage was widely observed from the boundary between the soil layer and the base rock. These results show that complex behaviors such as creep-like movements of the ground may be influenced by groundwater. Therefore, hydrological observation in underground will be conduct together with ground displacement observations to clarify the mechanism of ground displacement.

P1.3

EXPERIMENTS ON SUBMARINE GRAVITY FLOWS OF LIQUEFIED SAND IN A DRUM CENTRIFUGE

Junji Miyamoto[1], Shinji Sassa[2], Hikaru Ito[3], Ryoya Makino[3]
[1]Toyo Construction Co., Ltd., Technical Research Institute, Naruo, Nishinomiya, Japan, [2]National Institute of Maritime, Port and Aviation Technology, National Research and Development Agency, Port and Airport Research Institute, Yokosuka, Japan, [3]Toyo Construction Co., Ltd., Japan

Purpose: Submarine gravity flow of seafloor soil deposit is an increasingly important subject for research in relation to the stability of the offshore wind power facility, submarine cable and foundations of offshore structures as well as its devastating consequence on tsunami generation. The purpose of this study is to examine the behaviour of subaqueous gravity flows of liquefied sand in a set of centrifuge model tests.

Methods: The behaviour of gravity flow is mainly governed by the gravity acting on the sediment. Usual flume tests under 1g condition cannot reproduce in-situ gravity flows due to a much smaller mass of the sediment than a proto-type one. The centrifuge model testing technique is a realistic means of reproducing a submarine gravity flow. Furthermore, a drum-type centrifuge does not have side walls of the channel, so that long-distance flows could be observed (Figure 1). A series of flow tests was performed under centrifugal accelerations of 30g - 70g, in variation of particle size and thickness of initial sediment. The sediment having a thickness was liquefied and fluidized by upward seepage flow, and the gravity flow generated following opening the gate set in the channel.

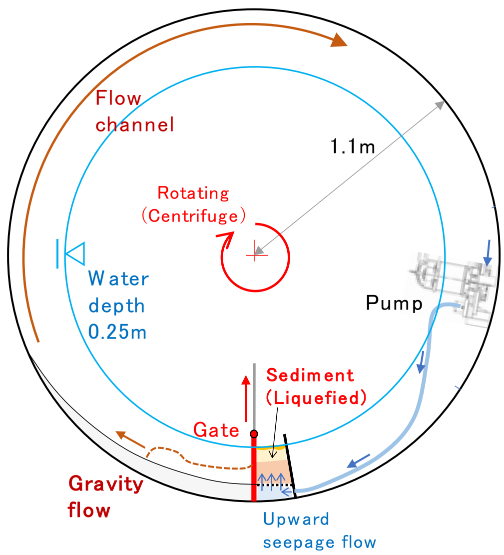

Fig. 1: Cross-section of a water channel inside a drum centrifuge.

Results: Sediment gravity flow with a velocity of 2.0 m/s, following liquefaction of 5 m-thick sand bed on the prototype scale, was reproduced in the drum centrifuge channel. The sediment flow, corresponding to fine sand in a field, travelled over a long distance with a constant velocity, resulting in a flow of more than 340 m on the prototype scale (the length of the experimental channel). We could observe variation of excess pore-pressures in sediments of liquefied gravity flows. Indeed, in the liquefied sediment flow, which corresponded to coarse sand in a field, the total stress of the sediment rapidly increased, but the excess pore-pressure in it did not increase, indicating that a rapid sedimentation took place with the effective stress development as the solidification proceeded. In contrast, in the liquefied sediment flow, which corresponded to fine sand in a field, the increase of the total stress was much smaller than the case for coarse sand, showing that the sediment flow substantially elongated with the slow dissipation of the excess pore-pressure as well as the slow recovery of the effective stress in the sediment.

Conclusions: Sediment gravity flows of liquefied sands with a variety of particle sizes and thicknesses of initial sediments were reproduced in the drum centrifuge channel. The dissipation of excess pore-pressures and the increase of effective stresses in the liquefied sediment flows could be observed during the entire submarine gravity flow processes.

P1.4

LANDSLIDE RESEARCH AND TECHNOLOGY IN PATENTS AND INTERNATIONAL STANDARDS

Matjaž Mikoš
University of Ljubljana, UNESCO Chair on Water-related Disaster Risk Reduction, Ljubljana, Slovenia

Purpose: A review on landslide research and technology in two types of documents: patent documents and international standards and dissemination of the results of this review to world landslide community.

Methods: Web survey of the relevant web databases yielding patent documents and international standards related to landslide disaster risk reduction.

Results:
Results of the study were published in two recent articles in P-LRT books:
- Mikoš M. Landslide Research and Technology in Patent Documents. In: Alcántara-Ayala, I. et al. Progress in Landslide Research and Technology, Volume 1 Issue 2. Progress in Landslide Research and Technology. Springer, 2023; Cham. 29-48. https://doi.org/10.1007/978-3-031-18471-0_3
- Mikoš M. Landslide Research and Technology in International Standards. In: Alcántara-Ayala, I. et al. Progress in Landslide Research and Technology, Volume 2 Issue 1, 2023. Progress in Landslide Research and Technology. Springer, Cham. 13p. in print.

Conclusions: The analysis of landslide-related patent documents, using three patent databases (Escapenet, Google Patents, Derwent Innovation Index) was performed to assess to which extent landslide science and technology is mirrored in patent applications, and what is the share of academic versus non-academic institutions. In the second part of the analysis, technical fields of patent applications were studied and countries that are the most productive ones with regard to landslide-related patent applications were searched for. The study finished by patent citation analysis in published scientific literature. The existing landslide-related international standards are concentrated to landslide prevention on one side, and on the other side to field and laboratory methods for soil and rock investigations and technologies to design and execute mitigation measures, and on supporting building codes. Many more options are open to work on new standards to support landslide disaster risk reduction, locally and globally. Taking both articles into consideration, further such studies are needed to enlighten the present state-of-the-art status of landslide research and technology around the world from this rarely used perspective (patents & standards). The International Consortium on Landslides with its global membership may take a more active role in this regard in future as a part of its voluntary contribution to the Sendai Framework for Disaster Risk Reduction 2015-2030 within the activities of the Kyoto 2020 Commitment for Global Promotion of Understanding and Reducing Landslide Disaster Risk.

P1.5
DIFFERENT PERCEPTIONS AND ACTIONS OF LANDSLIDE-PRONE COMMUNITIES WITH ESTABLISHED EARLY-WARNING SYSTEMS IN THE PHILIPPINES

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Department of Science and Technology - Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS)

Purpose: Understanding how people perceive risk has become increasingly crucial in disaster risk reduction and management (DRRM) programs, especially for improving early warning systems (EWS) and risk communication strategies. This study recognizes that various cognitive, social, and behavioral factors influence risk perception. Another perspective of this work is how risk perception relates to motivation to take protective action against a natural hazard (or landslide as a threat).

Methods: Using case studies in four study sites, this research analyzed how differences in influencing factors of risk perception affect the communities' sense of responsibility and actions towards DRRM and EWS activities. Qualitative data gathering methods such as focus group discussions, participatory workshops, community mapping, and interviews were applied to capture the risk perception of communities at-risk in the sites, namely, Pange village in Matnog, Sorsogon; Kinarum village in Magpet, Cotabato; Bacong village in Tulunan, Cotabato; and the village of Lipata in Paranas, Samar. The study sites have different landslide hazard experiences, spatial differences in exposure, and varying levels of engagement with the Dynaslope Project. The Dynaslope Project of the Department of Science and Technology - Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS) operates an EWS for deep-seated landslides through landslide sensor technology and community participation.

Results: The residents generally linked the term risk to danger, fear, and anxiety. These were associated with experienced hazards, and their relative location to the landslide hazard zone. Results also reveal that varying influential factors such as previous hazard experiences, risk communication, trust, landslide hazard awareness, and sense of place shape the perceptions of the communities in the study sites. (Re)actions to perceived risk range from mere acceptance of EWS to motivations and active participation of community members. These include participation in workshops and seminars, active monitoring (e.g., observation of surficial ground movement), and developing response capabilities such as drafting and implementing DRRM and evacuation plans.

Conclusions: The findings from the four case study sites show that experiences, level of exposure, and external and local interventions positively contribute to the risk perception of local communities. Continuous engagements and activities related to DRRM, regardless of who conducts or spearheads, help promote sustainable actions from local stakeholders.

P1.6
CRITICALLY REFLECTING ON ENGAGING COMMUNITIES FOR ESTABLISHING COMMUNITY-BASED EARLY WARNING SYSTEMS FOR LANDSLIDES

Jesusa Paquibot[1], Harianne Gasmen[1], Karl Daniel Begnotea[1], Jacquelyn De Asis[1], Melody Teodoro[1], Roy Albert Kaimo[1], Pauline Pagaduan[1], Arturo Daag[1], Teresito Bacolcol[2]
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Purpose: The Philippine Institute of Volcanology and Seismology (PHIVOLCS) - Dynaslope Project aims to contribute to the resilience and empowerment of Filipino communities by using science and technology in developing community-based early warning systems for landslides (CBEWS-L). The Project recognizes the key roles of local stakeholders in the CBEWS-L and conducts education and research activities to build the capacities of communities. The Project, however, has to examine its praxis of community engagement for establishing CBEWS-L by reflecting on how Project practitioners engage communities. Critically reflecting on Dynaslope's community engagement can provide insights into creating empowering strategies for CBEWS-L.

Methods: This research uses critical reflection as a crucial aspect of the continuous action-reflection-action cycle of community engagement for establishing CBEWS-L. Practitioners explore, learn from, and develop their praxis in the critical reflection process. During the group reflection dialogue, co-researchers as critical reflection groups establish a group culture suitable for learning and reflection. The group culture veers away from assessment or problem-solving but instead focuses on the analysis of community engagement. The session has two stages: the analytical stage where they examine the fundamental assumptions on the significant events and critical incidents from community engagement experiences, and the change stage where they articulate change awareness (whether to affirm, reframe, modify, improve, or rework their assumptions) and identify changes in thinking, actions, and strategies and label their praxis. Co-researchers dive into the analytical and change stages of the reflection process using creative qualitative research tools, specifically journaling and photo elicitation.

Results: In establishing CBEWS-L, practitioners navigate power dynamics when engaging communities where they encounter structural barriers to empowerment. Critically reflecting on creating and claiming spaces of shared empowerment or enabling structures is a necessary step in facilitating collaborative citizen science. Based on the critical incidents, Dynaslope strives to practice collaborative citizen science but recognizes limitations in terms of participation, organizational processes, and cultural difference. While individuals attempt to exercise "power within," doing so is not always enough to tip the scales of power, especially when working with Local Government Units (LGUs) and when capacities are yet to be built. Recognizing the constraints to collaborative citizen science and community empowerment helped us strategize community engagement activities. For example, critically reflecting on the power dynamics in the multistakeholder approach, the practitioners articulated the approaches, possible activities, and desired outcomes in mainstreaming EWS-L, which can enhance and sustain the local stakeholders' participation in CBEWS-L.

Conclusions: For a Project that continually implements activities and strategies, it is crucial to take time for critical reflection to raise the practitioners' awareness of their praxis and make intentional contributions to change. During the reflection sessions, the group identified outcomes that they want to see based on their praxis. Critical reflection is a venue where practitioners can discuss the critical incidents that emerged from engaging with stakeholders and articulate their praxis. It provides a starting point for aligning strategies to the interests of the stakeholders, relevant in advocating their ownership of the EWS.

P1.7
THE SEARCH FOR LITTLE ICE AGE LANDSLIDES IN BRITAIN

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Purpose: The presentation describes a project that owes its origins to a commonly-held opinion that the past climate in Britain during a period colloquially known as ‘The Little Ice Age’ (LIA) was conducive to the occurrence of landslides generally, and large landslides particularly. An understanding of future responses to weather, climate and indeed sea level must be informed by such a review as this of the past incidence of landslides as well as by studies of the spatial distribution of past landslides through ‘landslide inventories’. Indeed, in one example described in the presentation, a suspected area of landslide activity affecting a housing development was confirmed by a single newspaper report to have been a landslide affecting a long-abandoned railway line. Even this one example demonstrates the relevance of archival studies of past landslide incidence.

Methods: Much of the scientific literature on landslides in the study area postdates the dates that bound the LIA, and so the study therefore concentrates on newspaper accounts from about 1700. The methodology consists largely of a keyword search of online newspaper archives, followed by a study or the reports thus found.

Results: Results of the study and analysis of its findings include relationships between frequency and magnitude of landslide events, the incidence of fatalities, the temporal distribution of landslides reported in the press, and the relationships between the causes of the landslides. Reported landslides include ‘first time’ failures and the reactivation of pre-existing landslide systems, often themselves of considerable age.

Conclusions: Key factors in the incidence of landslides include the development of industrialisation with associated needs for materials extraction and waste disposal, together with developments of the transport infrastructure involving earthworks and excavations. The developments in geotechnical science and practice from the mid 20th century probably account for some of the diminution of landslide related incidences and fatalities, although the largest fatality count occurred with the entirely avoidable Aberfan mine waste tip collapse in 1966. The Aberfan disaster was a failure of not only bad practice that led to the event, but also to some reactions to the landslide as it progressed. As an aside, the commonest term used in the past was ‘landslip’, with ‘landslide’ only occurring first in the UK in 1891, although it had been used in the Press in the US as early as 1838.

P1.8

LANDSLIDES IN POPULAR CULTURE IN THE BRITISH ISLES: EXAMPLES FROM FICTION

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Kingston University London, Centre for Engineering, Environment and Society Research, Kingston upon Thames, United Kingdom

Purpose: In landslide hazard assessment, it is often found that human actions and behaviour can affect the levels of risk and therefore consequences such as the level of fatalities. It is therefore important to understand the factors that modify the behaviour of individuals and society not only in respect of the perception of hazard, but also their responses to hazard. Although short public information films on TV may well be useful, after a while they are ignored. Individuals gain information on behaviour subliminally, from what they read or see, or from the press or other media that catch their attention, or from social interactions. The media include art, books, newspapers, TV and radio, films and musical lyrics. Individuals learn from accounts of personal experience from social contacts, but in settings where landslides are relatively few and far between, there may be little experience to share. Landslides feature in art perhaps more often than is realised, because as well as renditions of landslides as the main subject, there are illustrations of landscapes (such as coastlines) in which the landsliding is merely incidental. In such cases, the landslide is predominantly a landscape feature rather than an event. Landslides feature in both live action and animated cinematography, again largely as a plot element associated with an event from which those involved escape (or do not) with some difficulty, but occasionally as a landscape setting (e.g. Pride Rock in The Lion King, which is a topple and is probably unnoticed by most viewers). The lyrics associated with song, particularly in popular music, permit only abbreviated mentions, sometimes only en passant. In contrast, when landslides feature in fictional literature, more often than not that it is an event which moves the plot along, with the length of a novel, for example, permitting more or less detailed accounts of the landslide itself and its impact on the protagonists in the book who can do more than simply escape from the scene. Usually, the description includes the emotional response of those protagonists as well as what they actually do.

Methods and Results: There are many books, most of which are unread by the Authors and most of which also do not contain accounts of landslides or even of other geohazards. The paper considers what can be learnt in the way of mitigation of landslide-related hazard from examples taken from a very small, random sample of widely-read popular fiction written by UK-based authors, and includes the responses to failures in natural slopes and infrastructure earthworks.

Conclusions: It is suggested that the increasing prominence of landslides in non-fiction (i.e. predominantly news) media will result in more frequent instances being written into new fictional works. Within the fictional context, it may be expected that there would be more mentions of key hazard and risk factors, thus gradually widening the general public perception of landslide hazards and so implicitly enhancing societal risk management.

P1.9

INTRODUCING JAPANESE LANDSLIDE WARNING SYSTEM TO SRI LANKA: FIELD SURVEY FOR ANALYZING THE AVAILABILITY OF MAP INTERPRETATION FOR SUCCESSFUL TECHNOLOGY TRANSFER

Kumiko Fujita
International Consortium on Landslides

Purpose: The central highland in Sri Lanka has the landslide prone geo-hydrological condition originally. Since the area have been developed for agriculture and human settlements, series of landslide occurred in the mid-1980s. Landslide is a natural hazard triggered by rainfall and geological condition. Since the topography such as mountain with steep slope and weather such as high precipitation are similar in Japan and Sri Lanka, similar landslide phenomena have been seen. One of the common landslide phenomena is Rain-induced Rapid and Long-travelling Landslide (RRLL). Recently landslide disaster risk reduction technologies have been developed in Sri Lanka, and foreign technologies have been introduced. Early warning and evacuation using hazard zonation map is a major system for landslide disaster risk reduction both in Japan and Sri Lanka. Japan have already developed and used the early warning and evacuation system using hazard zonation map. Since the system have been developed based on the Japan's socio-economic background, it is used successfully in Japan. Thus, when this Japanese technology is used in Sri Lanka, in addition to the engineers' availability of mastering technologies, local people's availability of accepting the technology is also examined before the project start.

Methods: In this research, social background for introducing Japan's early warning system in Sri Lanka is analyzed based on the literature review and field survey at Arayanake, especially focusing on the availability of map interpretation. Based on the literature review, it is said the map education is available. The questionnaire survey was conducted at Arayanake to know the local people's perception of landslide disaster risk reduction. There are five categories of questions as follows:

1. Demographic information: Q1-11
2. Livelihood: Q12-14
3. Experience of landslide: Q15
4. Hazard map and early warning: Q16-29
5. External help: Q30-36

Results: In the selected areas, there were 50 respondents, 16 males and 34 females. Based on the survey, it shows the availability of map interpretation. Twenty-eight respondents answered that they saw the hazard map of their living area. They are well educated to interpret the map, and many of the 28 people can tell the locations of their houses on the hazard map.

Conclusions: Since the availability of map interpretation is the must for landslide early warning system using hazard map, there is possibility that Japanese type early warning and evacuation using hazard zonation map is effectively used in Sri Lanka. However, hazard map in Japan includes the evacuation area and route, the survey for evacuation area and route is needed. In addition, information system for warning is also needed to be surveyed for utilizing the Japanese landslide warning system in Sri Lanka.

P1.10

RESEARCH AND DEVELOPMENT OF CORE TECHNOLOGY AND ITS APPLICATION FOR EARLY WARNING IN LANDSLIDES - INTRODUCTION OF THE SINO-JAPAN COLLABORATION PROJECT

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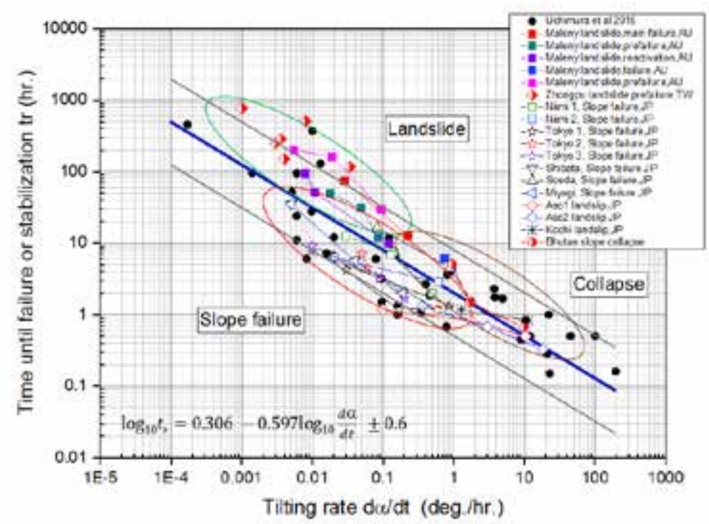
Purpose: Slope monitoring and early warning systems (EWS) are promising approaches to mitigating landslide-induced disasters. Many large-scale sediment disasters destroy infrastructure and loss of human life. The mitigation of vulnerability to slope and landslide hazards will benefit significantly from early warning alerts. Through the Sino-Japan collaboration project of the Japan International Cooperation Agency (JICA) and the Ministry of Science and Technology of China (MOST), a core technology of ‘A risk evaluation method of unstable slopes using multipoint tilting sensors’ is applied in Yangtze river basin. Establish an early warning threshold for landslide disasters due to rainfall, develop an early warning system, and demonstrate an experiment in China.

Methods:

The authors have been developing monitoring technology that uses a Micro Electro Mechanical Systems (MEMS) tilt sensor array that detects the precursory movement of vulnerable slopes and informs the issuance of emergency caution and warning alerts. In this regard, the determination of alarm thresholds is very important. The authors prefer tilt sensors and have proposed a novel threshold for the tilt angle, which was validated in this study. Additionally, multi-point monitoring has recently emerged and allows for many sensors to be deployed at vulnerable slopes without disregarding the slope’s precursory local behavior. With this new technology, the detailed spatial and temporal variation of the behavior of vulnerable slopes can be determined as the displacement proceeds toward failure.



Results: Forecast of the remaining time until landslide and slope failure as shown in the following figure which has considered landslides, slope failure, collapse, and field experiments since 2004. While the overall trend of the obtained data in the figure is similar to the Saito model, it is further proposed that three different failure times may affect the plotted relationship by our recent research.

$log_{10} t_r = 0.306 - 0.597 log_{10}\ da/dt \pm 0.6$

where tr denotes the time remaining until failure (hours) and dα/dt denote the rate of the tilting angle (degree/hour).

Conclusions: This paper introduces the most recent development of the authors’ EWS based on data obtained from several sites and their interpretation. As for the actual plans, the authors are currently undertaking the National key R&D project of Sino-Japan “Development and demonstration of monitoring and warning technology for the rainstorm induced mountain torrent disaster chain”, which takes the rainstorm-flood-landslide-debris flow disaster chain as the research object and is carrying out through international cooperation and joint research. The results such as deeply exploring the occurrence and evolution mechanism and developing the key technologies for precise monitoring and dynamic warning of the rainstorm-induced mountain flood disaster chain are expected to be obtained. The project aims to provide scientific and technological support for the mountain flood disaster chain prevention and control, and effectively improve the theoretical and technological level of disaster prevention and reduction research between China and Japan.

P1.12
CATASTROPHIC LANDSLIDES AND VICTIMOLOGY. COMPARATIVE LEGAL RESPONDE IN SPAIN AND ITALY

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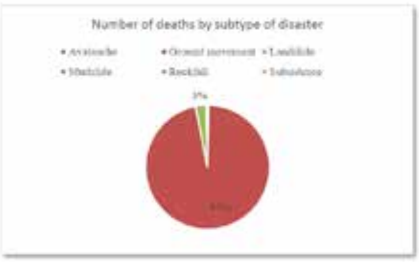
Purpose: Landslides and other catastrophic slope events are frequent worldwide, although in some areas they are clearly more frequent and with higher numbers of casualties. A table summarising events by type, continent, number of casualties and percentages of events with more than 100 casualties per subtype of event is included on the following page. It is included in the results as a preliminary to the intended work. The aim is to focus on landslides with fatalities or with catastrophic consequences in Italy and Spain. We will analyse, from a comparative law perspective, the problematic aspects of the punitive-punitive legal response model, centred on the conduct of the perpetrator and limited by the principles of guarantee, in contrast to another model centred on the reparation of damage to victims and the environment, which can be substantiated both within and outside the sphere of criminal law. Examples of cases involving victims include the cases of Vallliont (1963) and the derailment of the Val Venosta railway track on 12 April 2010 in Italy and the landslide at the Biescas campsite in 1996 in Spain. As an example of a catastrophe with multiple social and economic consequences, the Aznalcóllar dam breach in 1998 in Spain, one of the cases that gave rise to European legislation on Environmental Liability.

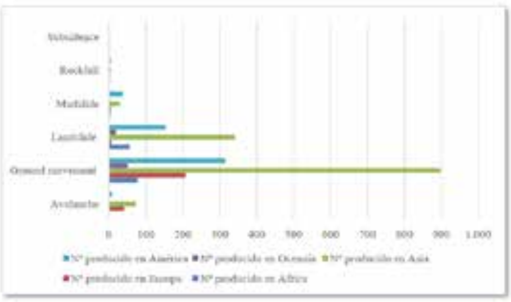
Methods: International databases such as EM-DAT of the University of Leuven in Belgium will be consulted. The following section includes a summary table based on consultations carried out in previous Works. Likewise, legal databases will be consulted to obtain, among other issues, relevant judgements, directly applicable European regulations transposed to Spain and Italy and specific legislation of each country regarding disaster law (CENDOJ, EURLEX, ITALGIURE), as well as doctrinal analyses (TOL, DEJURE). Specific aspects of how cases involving victims that reach the courts are resolved will be analysed, especially issues relating to the subsumption of events in the legal description of offences, negligence in its different degrees and the liability of perpetrators and participants. A selection of relevant cases in Italy and Spain will be made. An unavoidable case is that of Vaillont, which in Spain was used in one of the few criminal cases in which the criminal type on the creation of catastrophic risk was used.

Results: The following table is an example of previous work, which this proposal will complete from the fields of Criminal Law, Criminology and Forensic Geosciences.

Conclusions: The intention of this proposal is to make a comparative law study on the criteria of imputation in cases of landslide disasters "sensu lato" in Italy and Spain, integrating scientific and technical aspects that contribute to the perspective of Risk Management and Disaster Risk Reduction (MR&DRR) in order to minimise casualties. The interdisciplinary team is composed of specialists in geology and geological engineering, criminology, environmental sciences and agricultural engineering and environmental criminal law.

Number events produced of the different subtypes of disasters in each continent.
Source: Díaz Vega, Marta & Zango-Pascual, Margo (2022): Analysis of catastrophic landslides and its relations with the survival rate, from the perspective of forensic geosciences (Final Project of Degree in Environmental Sciences. UPO. Unpublished)





Subtipe of disaster	Number of events with deaths	Number of events without fatalities	% of events with deaths	Number of events with more than 100 deaths	% of events with more than 100 fatalities
Avalanche	118	3	97,5	15	12,39
Ground movement	1.155	391	74,7	316	20,44
Landslide	549	26	95,5	85	14,78
Mudslide	71	4	94,7	11	14,67
Rockfall	12	0	100,0	1	8,33
Subsidence	2	0	100,0	1	50

P1.13
SENSITIVITY ANALYSIS OF SHALLOW LANDSLIDE PREDISPOSING FACTORS ON TERRACED SLOPES IN THE DOURO VALLEY

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Purpose: The study area is located on an estate in the village of Pinhão within the UNESCO World Heritage landscape of the Douro Valley (Portugal). The vineyards (74.6 ha) are organized in terraces, predominantly south-facing, with altitudes ranging between 62 and 394 m. The area has a Mediterranean climate type with an annual average rainfall of 658 mm. Recently, the estate developed a renovation process with the re-construction of land embankments, mostly from large 2 rows terraces to narrow terraces (1 row), along with new drainage systems. These changes on soil physical conditions promoted water erosion and slope instability. An extraordinary rainfall episode occurred on 26th December 2022 triggered a multiple landslide event affecting the renovated areas. The main purpose of this work is to stablish statistical relations between an event landslide inventory and a set of predisposing and triggering factors that control slope instability in man-made slopes.

Methods: Methodology was developed in 5 mains steps. (1) Characterization of the critical rainfall triggering conditions of the landslide event, through the computation of I-D rainfall thresholds considering the RP; (2) Development of a landslide event inventory (location, area, length and volume) using field work and ortophotomaps (10x10 cm); (3) Creation of landslide predisposing factors datasets of the general slope (slope angle, slope aspect, slope curvature), terraces morphology (cut slope heigh and angle, platform weight and angle) and hydrological works on slopes (diversion channels, paths) derived from a detailed DEM (10 x 10 cm); lithology, soil texture and soil depth estimation; (4) Perform a logistic regression analysis to assess each predisposing factor importance to explain landslide susceptibility; (5) Computation of the success rate curve to estimate the general quality of the model.

Results: This study was focused on an elongated sub-basin of 0.42 km2 which geological and morphological characteristics are representative of the whole study area. The altitude ranges from 85 m to 394 m and is mainly composed of stratified levels of phyllites, quartz metagreywackes and schist intercalations dating from the pre-Cambrian. Almost ~200 shallow translation slides were inventoried. The landslides show an unevenly distribution, being more concentrated in the upslope sector, characterized by a general convex morphology of the general slope, with higher cut slopes and where the remobilized antrosoil layer is deeper. The height of the affected terraces range between 1.5 m and 4 m. The length of the landslide main scarp range between 1.5 m to 50 m, with an average 12.4 m, exposing the vineyards roots, planted in the external border of the terrace platform. The heigh of the scarp is lower than 0.5 m and the mobilized material generally experiment a short displacement without surpass the lower terrace.

Conclusions: The work is a contribution to predict landslide susceptibility areas triggered by high intensity rainfall events, and to estimate future potential damages and economic losses associated with the vineyards production decrease on affected terraced slopes. These results may be applicated to adjust guidelines for terraces construction to avoid the effects of soil erosion and landslides.

P1.14
AN OPEN-SOURCE WORKFLOW FOR THE CLASSIFICATION AND MONITORING OF RIVER EMBANKMENTS: A CASE STUDY FROM THE ARNO RIVER (FLORENCE, ITALY)

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Purpose: Climate change is a critical phenomenon also established in Europe. Recent studies revealed a significant global warming, which induce an enhancement of climate variability and a general increase in frequency and intensity of extreme weather events [1]. Heatwaves and droughts are more frequent and intense, while heavy rainfall and flooding events are also increased. In Italy, where areas surroundings cities are often heavily urbanised and waterproof, flooding events are fairly frequently, with a high number of deaths and devastating effects for land, buildings and social assets on most of its territory. The Arno River basin in Florence (Italy) is a specific scenario of flood risk issues. Most of the territory is prone to flood hazards, with high levels of risk due to the vulnerability of a unique artistic and cultural heritage [2]. In this regard, it is important to disseminate timely warning information and perform regular maintenance of defence structures.

Methods: Embankments are complex structures characterized by their highly variable hydrologic and geomechanical properties, e.g., dry, partial saturation and full conditions (Figure 1).

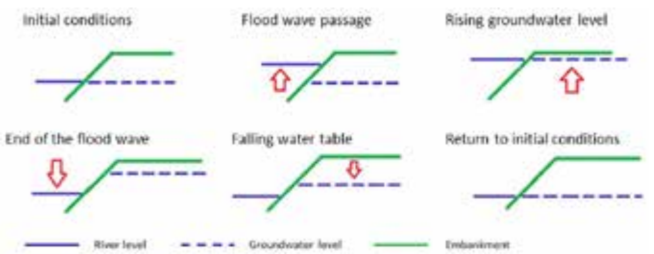

Fig. 1: Flood wave effects on groundwater and river level.

Fig. 2: Embankment instability propensity map.

The method proposed in this study is based on two main topics: the morphological and hydrogeological characterization of the Embankments and the stability analysis of these latter through the open-source software Slope Stability Analysis Program (SSAP). The goal of this work is to develop the safe factor maps along the Florentine stretch of the Arno River in different hydrologic conditions. This study was carried out using free public data.

Results: This work allowed the geologic and morphologic classification of the embankment sections along the Florentine stretch of the Arno River and the monitoring of their stability. A univocal method was established to create safety factor maps under different hydrogeological conditions. The riverbanks stability analyses demonstrate that the lower safety factor was obtained in the case of complete saturation of filling materials and low river level in accordance with the recent events occurred in Florence. Figure 2 shows the embankment instability propensity map realised considering the decrease in the safety factor from a situation of partial soil saturation to one of complete soil saturation and low river level.

Conclusions: Embankment stability monitoring is an essential component of hydraulic risk management and ensuring the safety of urbanized areas. Unstable embankments can fail and lead to significant flooding, cultural damage, and even loss of life. In urbanized areas, embankments may be compromised due to different factors, including erosion, sedimentation, vegetation growth, land use changes, and human activity. To prevent embankments failures and mitigate the associated risks, it is essential to constantly monitor their stability.

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P1.15

COMPLEX MONITORING SYSTEM FOR THE PROTECTION OF ROCK-CUT CULTURAL MONUMENTS OF GEORGIA AFFECTED BY GEO-HYDROLOGICAL HAZARDS

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Purpose: The geo-hydrological risk may have extremely devastating impacts on Cultural Heritage sites located in areas threatened by natural hazards caused by gravitational and fluvial dynamics. The Georgian rock cut heritage, such as the Rock Cut Cities and monastic complexes of Vardzia, Vanis Kvabebi, Uplistsikhe and Sabereebi (David Gareja), well represents a clear example of areas in which the above-mentioned processes are strongly active, harming the stability and conservation of the sites and also on their future tourist sustainable exploitation. In most of these cases, the geological composition of the sites is characterized by relatively modest geotechnical strength parameters (weak rock), convenient for curving into the rock of artificial cavities, but which today contribute to increased criticality in terms of stability of the present sub-vertical walls, chambers and rock slope facades. The above mentioned rock-cut cultural heritage sites of Georgia (also in tentative list for the UNESCO candidacy) require that study and monitoring should be conducted based on non-invasive low impact technics. Transfer of international experience and current developments in the field is important to support the high-resolution studies with minimal impact on the monuments (e.g. solutions with wireless and remote-controlled networks and sensors, UAV applications, long-range laser scanning). In recent years, a series of joint research activities were carried out in tight cooperation between the Italian and Georgian experts leading to increased knowledge of current state of the rock-cut monuments of Georgia, to monitor and identify the critical sites and processes.

Methods: Rock cut monuments were studied and monitored using several non-invasive technics:

- Complex online monitoring network of sensors, including: Extensometers, Strong Motion Sensors, Micro Climate monitoring sensors in caves (temperature and humidity) and Meteorological Stations.
- Topographic monitoring using the total station and reflectors permanently installed on the Rock Cut monument.
- Ground-Based Radar interferometry.
- Photogrammetric Aerial survey from drone.
- Long Range 3D Laser Scanner

Fig. 1: Location of case study.

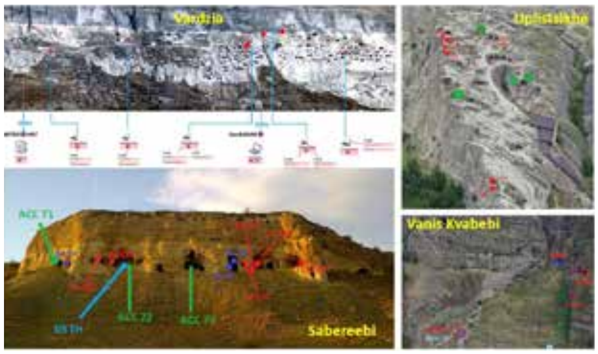

Fig. 2: Some examples of monitored sites.

Results: As a result of joint Italian-Georgian international effort comprehensive monitoring system was developed to safeguard Rock Cut Cultural Heritage Monuments of Georgia, involving multiple monitoring technics. The systems actually implemented, allow to have up-to-date information about the state of the monument, design and carry out proactive protection. Comprehensive monitoring system, with its technical and methodological components, which have been developed during the multi-year joint efforts can be applied to other similar Cultural Heritage monuments worldwide.

Conclusions: The monitoring and protection of Cultural Heritage sites from geo-hydrological instabilities can be a complex but important activity. Monitoring systems are fundamental tools for the characterization of active processes. Appplication of modern up to date technologies, and availability of several monitoring solutions can support this analysis, but it is important to couple the use of these instruments with an effective data management.

P1.16
30 YEARS OF CULTURAL HERITAGE LANDSLIDES AND BLOCK MOVEMENTS RISK ASSESSMENT: CASE STUDIES FROM EGYPT

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Throughout such rich history of civilization, Ancient Egyptian kings and queens had the habit to construct temples (to worship Goddesses and Gods) and dig tombs to commemorate their bodies and souls, in preparation for the afterlife.

In Egypt, throughout the ancient Egyptian Civilization, Egyptians have chosen to carve their temples and tombs in the soft limestone, shales and sandstones that are covering most of the modern Egypt, whereas in few temples and tombs, hard igneous and metamorphic rocks were used as ornament material for tombs and statutes.

In this paper, we will present an account of the development of landslide risk assessment for various cultural heritage sites around Egypt, for different eras of Egyptian history and different sites.

This paper aims at discussing different case studies and success stories of landslides and block movements hazards assessment around or inside the following Egyptian Cultural Heritage sites: The Temple of Deir Elbahari, the tomb of Ramses I, the tomb of the Serapeum.

P1.18

INTEGRATED INSAR MONITORING OF GROUND DISPLACEMENT ON ARCHAEOLOGICAL STRUCTURES AT THE ANCIENT PORT OF CLASSE (RAVENNA, ITALY)

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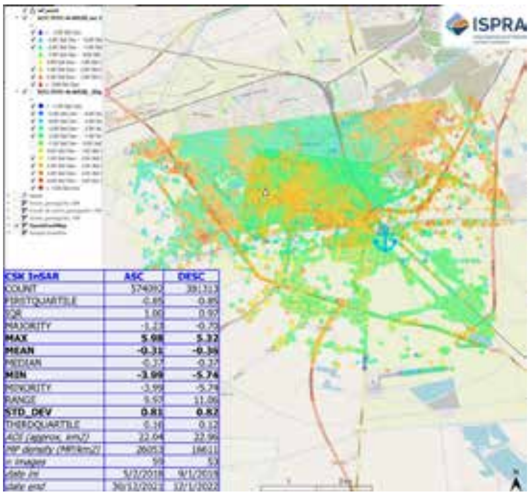
Purpose: The present work is part of the activities carried out jointly by ISPRA (Geological Survey of Italy) and Ministry of Culture (General Directorate for the Safety of Cultural Heritage) for the implementation of the first “Extraordinary National plan for monitoring and conservation of Italian cultural heritage”. The Plan is aimed at the conservation and protection of cultural heritage, and specifically on its protection against the impacts of different hazards, both anthropogenic and natural, including climate-induced extreme events. As representative of archaeological coastal settlements, the Roman Port of Classe has been selected for detailed investigations.

Methods: The area of Ravenna is affected by subsidence both natural (about 3 mm/year, due to the compaction of soft sediments and to the isostasy) and anthropogenic (up to 15 mm/year, mainly due to the extraction of methane gas). This is well demonstrated by GNSS and InSAR series lasting since 90s. Most recent ground displacements in the area of Ravenna was studied analysing two different InSAR dataset and referring this evolution to the historical trends obtained by GNSS network and by previous InSAR data. In this work have been analysed data from the European Ground Motion Service (EGMS), based on InSAR processing of years 2015-2020 Sentinel-1 SAR images (C band, medium spatial resolution), and an original InSAR dataset processed for the years 2018-2021 on Cosmo Sky-Med SAR images (X band, high spatial resolution). While the EGMS dataset is calibrated on a continental scale, the latter dataset have been referred to the local GNSS station, belonging to the regional network, thus highlighting local relative displacements, that can be referred to the real earth’s motion. The InSAR analysis have been integrated with a specific survey in order to check the actual evidences on the ground of features from remote sensing.



Results: The results of ground displacements monitored both from Sentinel-1 and Cosmo Sky-Med since year 2015 are in good agreement with previous studies, revealing a continuous overall settlement of about 5 mm/yr for the city area. The archaeological area of the ancient Port of Classe is not affected by significant differential ground displacements. Nevertheless, in the southern area of the city, not far from the ancient Port, some new commercial buildings seems to be affected by settlements up to about 10 mm/yr.

Conclusions: The comparison of wide area general ground motion InSAR data and local, high resolution measurements, integrated with geological data and structural inspections, provides an optimal monitoring approach for archaeological sites threatened by ground deformation.

P1.19

MULTI-SCALE PROTECTION AND CONSERVATION OF UNESCO CULTURAL HERITAGE AFFECTED BY GEO-HYDROLOGICAL HAZARDS

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Purpose: increasingly frequent landslide phenomena, also due to climate change, threaten the world's cultural heritage. Therefore, a monitoring of cultural heritage is necessary to mitigate the related risk. This work is focused on the implementation of an integrated multiscale methodology, based on the use of non-destructive diagnostic and remote sensing techniques, for the conservation and protection of cultural heritage affected by hydrogeological hazards.

Methods: the analysis of ground movements and structures via interferometric radar satellite sensors was carried out at a regional scale on cultural heritage sites characterized by complex geomorphological settings in Tuscany, Campania, and Lazio regions (some of them like Paestum and Pienza belong the UNESCO World Heritage List). A powerful and well consolidated method (Persisted Scatterer Interferometry=PSI) was employed and integrated with all the available thematic data (geological, hydrogeological, piezometric, etc.) and field surveys to fully interpret the deformative scenario of the survey sites. At the site scale the UNESCO Nabatean site of Hegra, carved in Cambrian quarzitic sandstone, was selected for plays its peculiar climatic, geological, and geomorphological setting, which makes the monumental tombs prone to erosion phenomena and slope instability. The aim of the research was to perform a the site, by integrating traditional geomechanical-geomorphological field surveys with non-destructive diagnostic techniques (infrared thermography), and rock sample for laboratory geotechnical analysis.

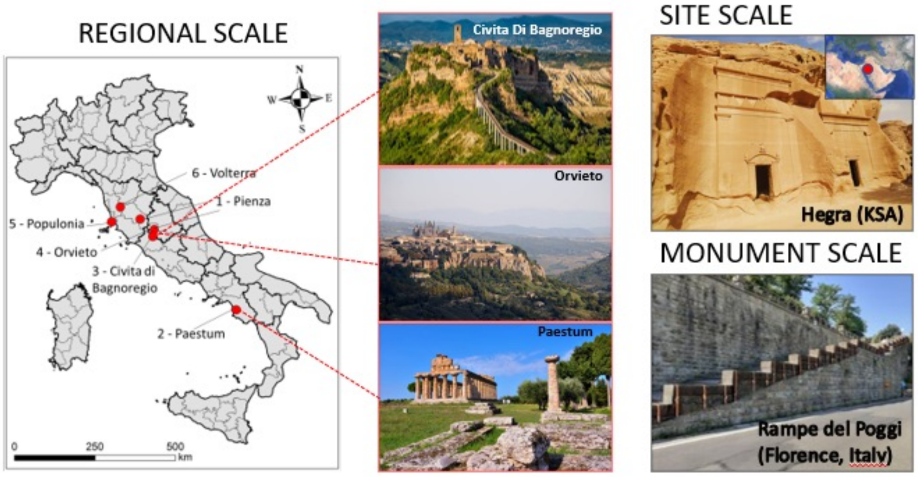

Fig. 1: Multi-scale protection and conservation of UNISCO cultural heritage affected by geo-hydrological hazards. Regional scale: interferometric radar satellite sensors on cultural heritage sites in Tuscany, Campania, and Lazio regions (some of them like Civita di Bagnoregio, Orvieto and Paestum); site scale: survey of the 138 tombs of the UNESCO Nabatean site of Hegra in Kingdom of Saudi Arabia; monument scale: stability analysis of stome elements on historic buildings of the Florence UNESCO centre (eg, the ramp of Piazzale Michelangelo).

At the monument scale a stability analysis was carried out on the single stone elements on historic buildings of the Florence UNESCO historic centre (e.g., the ramp of Piazzale Michelangelo). Here to establish the safe touristic fruition of the ramp stairway and street below a survey of fractures, joints, and degradation of the stones of the monument was performed.

Results: PSI data, based on the deformation rates, can be profitably used to quickly identify from a regional to a local scale ongoing slope instabilities and structural deformation to be used for planning of the priority of intervention of the most dangerous areas. In Hegra it was possible to map the spatial distribution of the tombs and understand their correlation (greater exposure to atmospheric agents or areas with different lithologies), while for the Ramp of Piazzale Michelangelo in Florence the mapping of joints-fractures was used to plan the priority of intervention for the mitigation of degradation and possible collapses.

Conclusions: the integration of remote sensing, diagnostic, and non-destructive techniques with traditional structural-geomorphological surveying of cultural heritage sites are indispensable for the identification of potentially unstable areas in order to carry out preventive maintenance, instead of expensive and often improper restorations.

P1.20

MAPPING GROUND INSTABILITY IN MEDIEVAL VILLAGES USING COMBINED TECHNOLOGIES FOR THE DEFINITION OF POTENTIAL LANDSLIDES SCENARIOS

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Purpose: Central Italy is famous for many historical towns that strew over the territory making it peculiar. Most of them were built, during the medieval age, mainly on the top of high and steep rocky plateaus with a consequent scenographic effect that made them recognizable and famous all over the world. Their position, on the top of high and steep cliffs, and their architectural development derive essentially from defensive reasons. Over the centuries this function has failed, but people have continued to live in these areas, making the most of every available space in harmony with its past history and the really sustainable development opportunities. The wise activity of man has preserved and protected them from neglect and abandonment as well as from the more recent urbanization. Despite the spectacular position, these centres have always been exposed to a high widespread degradation of the exposed slopes and high landslides/ rockfall risk. In this context, this paper aims to present an optimized approach for the study of potential landslide phenomena that affect these medieval towns using combined technologies. Monte San Martino, Penna San Giovanni, Smerillo and Montefalcone Appennino, located in the Marche Region, are used as case examples.

Methods: These towns, built on top of sandstone cliffs, are characterized by a similar geological evolution and morphology and have been affected by several landslide phenomena during their history. On slopes that have suffered a strong advance in these gravitative processes and show an advanced degree of geomorphological evolution, inaccessible areas have been created or, under the most mature conditions, soil accretions with localised vegetation have developed covering portions of the slope. To overcome the critical issues field survey and mapping have been carried out through the use of innovative digital mapping tools, so that to create a digital database with all field information. Data gathered during field surveys were integrated with GIS analyses for an improved interpretation of geological features at a larger scale. A more detailed analysis of high and steep slopes was performed through the use of UAV and A-DInSAR interpretation to verify potential active failures.

Results: Traditional field surveys were integrated with innovative digital mapping to obtain a detailed digital database in the GIS environment. The drone survey allowed to create 3D structural models of the high steep rock cliffs in order to identify the discontinuity system and estimate the volume of the blocks of rock masses that could be involved in landslides. Finally, the ground movements mapping and monitoring of their cinematic evolution in the less steep areas was obtained with A-DInSAR data analysis.

Conclusions: The combined use of these technologies allowed us to investigate the potential landslide scenarios and to improve the understanding of the failure mechanisms affecting the four medieval villages. Furthermore, this work can provide basic information for verifying the danger of collapse that the historical assets bordering the outermost limits of sub-horizontal terrains may suffer in the near future.

P1.21

MULTISENSOR REMOTE SURVEYS FOR THE STUDY OF LANDSLIDES AFFECTING THE UNESCO WORLD HERITAGE "TEMPIO DI GIUNONE" SLOPES ("VALLE DEI TEMPLI", SICILY)

Giovanna Pappalardo[1], Simone Mineo[1], Davide Caliò[1], Renato Macciotta[2], Sohrab Sharifi[2], Luigi Maria Caliò[3], Maria Concetta Parello[4]

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Purpose: This study focuses on the analysis of the landslides occurring at a UNESCO World Heritage Site, located along the southern coastline of Sicily (Italy). This archaeological area in Agrigento, named Valle dei Templi, covers the vast territory of the ancient polis and the sacred hill on which a row of Doric temples stands. The sacral complex is located on the top of an asymmetrical syncline, with an approximately northward-dipping E-W axis, made up of a Lower Pleistocene sandy-clay sequence with various calcarenite bodies. This lies on Middle-Upper Pliocene clay soils (Cotecchia et al., 2005). The Tempio di Giunione stands at the edge of the southernmost part of the calcarenite cliff, which shows signs of instability. Also, the clayey slopes have historically been affected by landslides (Cotecchia et al., 1995), testifying the engineering geological and geomorphological complexity of this sector.

Methods: The landslide study was carried out by airborne photogrammetry and multi-temporal InSAR (MT-InSAR) analysis. The photogrammetric survey was carried out according to two flight plans and 25 Ground Control Points were arranged for the correct geo-referencing. Frames were post-processed to build a dense point cloud and the main geostructural data were extracted according to a semi-automatic procedure for the kinematic and stability analyses. The MT-InSAR analysis was carried out through processing 154 ascending and 207 descending SAR scenes archived by Sentinel-1 corresponding to 2016-2022. The 1D line-of-sight velocity vectors for each year were then converted to 3D total velocities by assuming that movement kinematics follow the aspect of slopes.

Results: The digital rock mass analysis allowed identifying the major instability features affecting the Tempio di Giunone cliff and the analysis of the most recurring failure patterns returned unstable safety factors. Moreover, the collapsed volume estimation allowed evaluating a front recession to be compared with data available in the literature. MT-InSAR results allowed mapping key spots affected by movements along the clayey slopes which are located on the immediate eastern slope of Tempio di Giunone cliff and fan-shaped eroded areas on the southern aspect. It is also observed that the maximum intensity of rainfall episodes correlates with the extent and activity level of deforming areas.

Conclusions: Achieved results demonstrate that the landslides affecting this area are still active and represent a threat for the archaeological site located at the cliff edge. Rockfall major instability features involve rock volumes even greater than 2.5 m^3. This volume is indicative of potential detachments, although the greatest surveyed collapsed block has an approximate volume of 640 m^3. Moreover, the occurrence of movements affecting the slopes underneath the Tempio di Giunone cliff suggests a complex and dynamic slope evolution, which needs to be monitored for risk management and safe heritage fruition.

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THEME 2

REMOTE SENSING, MONITORING AND EARLY WARNING

P2.1

FULLY INTEGRATED UAV LIDAR FOR THE MONITORING OF LANDSLIDES IN EMILIA-ROMAGNA REGION

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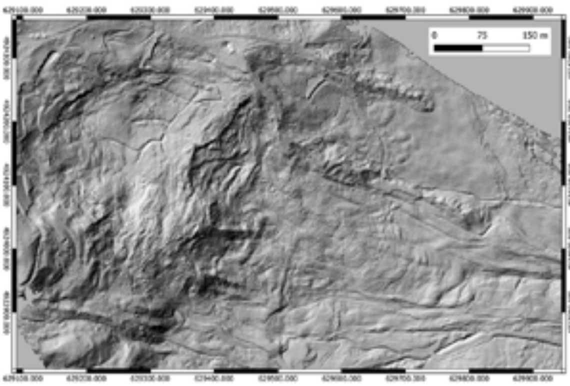
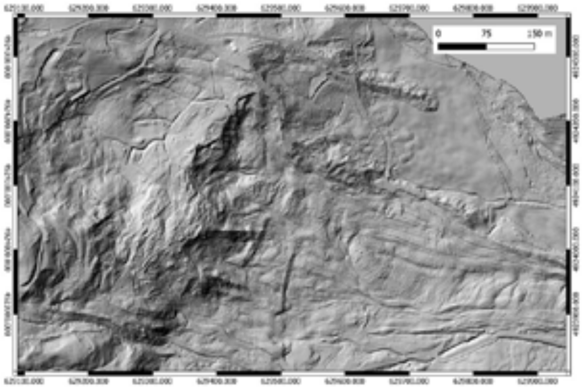
Purpose: The airborne Unmanned Aerial Vehicle (UAV) Light Detection and Ranging (LIDAR) is one of the most effective methods to monitor large landslides. Here we describe applications of it in Emilia-Romagna region. Since 2019 the local Civil Protection Authority directly manages a drone Matrice 300, the LIDAR sensor L1 and the processing software TerraSolid, with more than 60 surveys done. This remote-sensing instrumentation allows to detect movements of landslides by comparing multiple scans taken at different times, at the same altitude and tracking the same trajectories.

Methods: Unlike aerial photogrammetry, the LIDAR can "see" under vegetation. Laser impulses detect the vegetation, but they also go through the foliage before returning to the sensor, so assessing the position of the ground. A peculiar inflight feature of the L1 LIDAR sensor is the possibility of tilting on the XYZ axes. So, doing several low passes (usually 40 m, with different tilt angles of L1), it is possible to penetrate the vegetation reaching a good rate of "ground" points. Even under a full forest cover and after a complete noise reduction, a number of 25-30 "ground" points per square meter can be obtained. In these conditions of survey, our recent tests demonstrate that also dense grass is not a significant obstacle. Post-processing produces point clouds that can be classified, allowing to extract the "ground" level from other objects as buildings, trees, bushes and even grass. The software allows to do this in automatic mode, but manual intervention is always needed. In particular, we need to force the software to classify as "ground" those points pertaining to several artifacts that the software correctly would classify as retaining walls, gabions, draining wells and roads. These artifacts must appear in the DTM generated from the "ground" points cloud to act as references for detecting landslide displacements through time. In fact, the last file at the end of the process is the Digital Terrain Model (DTM), that is usually generated with a grid of 0.2-0.5 meter cells and can be managed by GIS.



Calita Landslide: DTM May 2022



DTM January 2023: displacement of 18 (left) and 80 (right) metres can be detected.

Results: The comparison of several "ground" Point Clouds and DTMs, taken in the same way and in the same way and position at different times, highlighted the evolution of the Large Calita Landslide in the Province of Reggio Emilia. Significant movements of it, occurred in the last year, gave us the opportunity to test the UAV-LIDAR technology. The presence of several other monitoring instruments that are available on the site (GPS, inclinometers, extensometers, UAV aerial photogrammetry) offers good reference for the assessment of the UAV-LIDAR data quality.

Conclusions: Images here shown illustrate as the comparison of DTMs taken at different times, through appropriated software, can describe the morphological evolution of Calita, in quantitative way. Present movements of the landslide, of decametric scale, are concentrated in the secondary scarp and triggers the underlying earth flow (on the right). In general, according to our experience, LIDAR multitemporal DTMs easily allow to detect displacements till 1 meter-scale.

P2.2

AN INTEGRATED APPROACH FOR THE STUDY OF A LARGE LANDSLIDE IN THE EMILIA APENNINES

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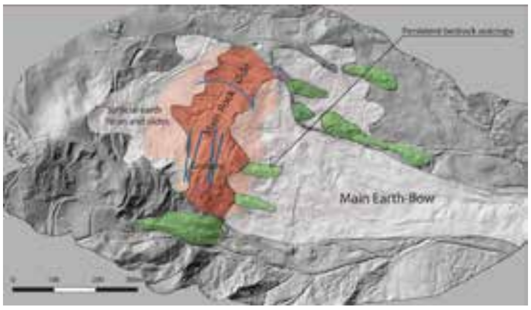
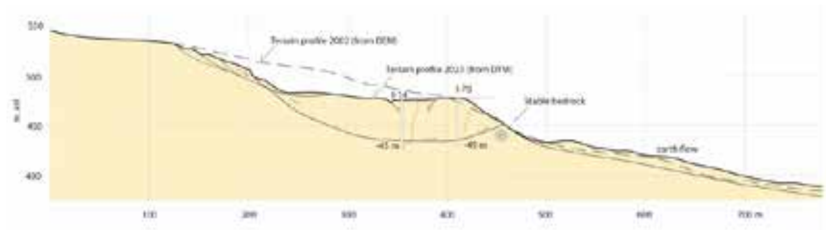
Purpose: Since its major reactivation in 2002, Calita has been one of the largest active landslides in the Northern Apennine and, after twenty years of continuous activity, it is still far from running out of energy. During this period, it was subject of an extensive set of studies and interventions aimed to slow down its activity and mitigate its dangerousness, but with limited results. Calita landslide has a length of about 2500m, showing the typical features of most Apennine landslides. A flysch rock mass of 1,7x106 cubic metres (the so called "Piana") moves from the top of the slope and his disarrangement feeds a long earth flow tongue (the so-called "Colata", 7x106 m3 in volume) reaching the valley bottom. Here we describe our recent integrated research, aimed to detect the features of the rupture surface underlying the flysch rock mass and its internal structure.

Methods: The new investigation includes geological drillings and surveys, deep seismic (refraction) and geoelectrical prospections, continuous groundwater pressure measurement, geotechnical laboratory tests, radiocarbon dating, on-site monitoring and remote sensing. These new activities have been underway since the 7 of May 2022, when the whole rock mass suddenly reactivated without precursor signs, moving about 19 metres in five days (18 metres on the horizontal plane and 4 in the vertical). Another unexpected reactivation occurred on the 4th of March 2023, when the "Piana" moved 7,2 metres in 5 days (6,8 in the horizontal and 2,5 in vertical). These two recent reactivations occurred after poor (2022) or insignificant (2023) rainfall.



Sketch map of the Calita upper part.



WNW-ESE cross-section

Results: Investigations are still in progress, but the first results indicate that the surface of rupture is situated at the maximum depth of about 43-49 metres and seems to have a concave shape, with a counter-slope attitude in the valleyward part. Above it, the rock mass slides with a significant rotational, clockwise component. At the base of the secondary scarp two clayey cusps, emerging from the mudflows and pertaining to the stable bedrock, form a sort of barrier to the movement. This peculiar shape of the rupture surface does not match completely with a simple "gravitative" origin and may be partly due to ancient tectonic "shaping" factors.

Conclusions: Over the past decades, a large net of 50 drainage wells (up to 40 m deep), has been built through the "Piana", without great results. A better understanding of its features (particularly the shape of the rupture surface, the rock mass thickness, the distribution of groundwater pressures) is a decisive/critical element to decide the most significative factors on which to intervene.

P2.3
LONG-TERM MONITORING AND EARLY-WARNING OF THE SIFANGBEI LANDSLIDE IN THE THREE GORGES RESERVOIR AREA

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Purpose: Long-term monitoring and early warning of reservoir landslides are crucial to reducing the risk of landslide disasters. The Sifangbei landslide is a rotational slide that has experienced multiple-sliding events due to regional structure, water level fluctuation, rainfall, and other factors such as infrastructure and farmland construction. The landslide area forms a micro-geomorphic type with a steep and gentle slope, developing four large deformation platforms. This work proposed a multidisciplinary approach to comprehensively understand the kinematic mechanism of landslides and apply the widely-popular landslide evolution model.

Methods: This work is based on a long-term research plan and has been implemented in the Sifangbei landslide in the Three Gorges reservoir area of China. The main innovation features are: (i) Global Navigation Satellite System, conventional inclinometer monitoring, and Persistent Scatterer Interferometric Synthetic Aperture Radar technology jointly analyzed the landslide displacement characteristics. (ii) a dynamic prediction model of landslide displacement based on long short-term memory (LSTM) neural networks. The Grey wolf optimizer optimized the hyperparameters of the LSTM model, and the dynamic one-step prediction was carried out for each displacement. (iii) The adaptive landslide evolution model was used to describe the evolution trend.

Results: The expected results show that: (i) The rear edge of the landslide has had no deformation in recent years and was not significantly affected by periodic factors (e.g., rainfall and reserve water level). The landslide deformation was mainly concentrated in platforms I and II. (ii) The deep learning algorithms obtained the optimal prediction model of landslides at different spatial locations. (iii) the five-stage evolution model could well capture the long-term evolution trend of reservoir landslide, as well as the skills of landslide prediction and the establishment of the early warning system.

Conclusions: In particular, the proposed comprehensive monitoring and early warning seem to help develop real-time control and risk mitigation strategies in the short term. Considering many unstable slopes with similar geological backgrounds in the Three Gorges reservoir area, the proposed research framework can provide a reference for the government's risk management strategy.

P2.4

COMPARISON OF C-, X- AND L-BAND DIFFERENTIAL INTERFEROMETRY RESPONSE: DOBKOVIČKY LANDSLIDE CASE STUDY

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Purpose: The aim of the study is to verify the suitability of the simultaneous usage of C-, X-, and L- band radar-based interferometry for updating the landslide inventory in Elbe valley, a landscape highly prone to instabilities. The radar wavelength is one of the defining parameters of the radar images, which has direct effect on the depth of penetration and interaction with objects on the surface.. Radar interferometry techniques applied to radar data of multiple bands can provide different information with respect to the variability of surface types. As a study site, the large scale Dobkovičky instable slope, has been selected. The area is a subject of long-term monitoring, and is famous for major landslide destroying part of the under-construction E55 motorway in 2013. The cover of the studied area consists of heterogenous surfaces, such as anthropogenic (highway body, quarry, buildings), rural and wooded areas.

Methods: To study the suitability of the different radar bands, an annual time series of 58 freely available Sentinel-1 images of 2021, 4 TerraSAR-X images from autumn 2022 and a series of 5 ALOS-2 images, each with a year interval, from 2017 to 2021, have been deployed. Conventional differential interferometry (DInSAR) is applied to X- and L-band image pairs due to low number of available data, the C-band data is processed using advanced Persistent scatterer interferometry (PSI).

Results: Using the C-band data (PSI method), a subsidence of up to 10-13 mm per year was found on the highway body (Figure 1A), and also in the lower parts of the slope. Using the X-band data, the largest subsidence up to 1 cm was detected in the nearby quarry (Figure 1B) with other deformations found along the highway. The deformation raster based on ALOS-2 data highlighted deformations at locations that are incoherent at other wavelengths (Figure 1C). These were mostly forested slopes west of the highway. The similar spatial pattern was shown in different time periods.

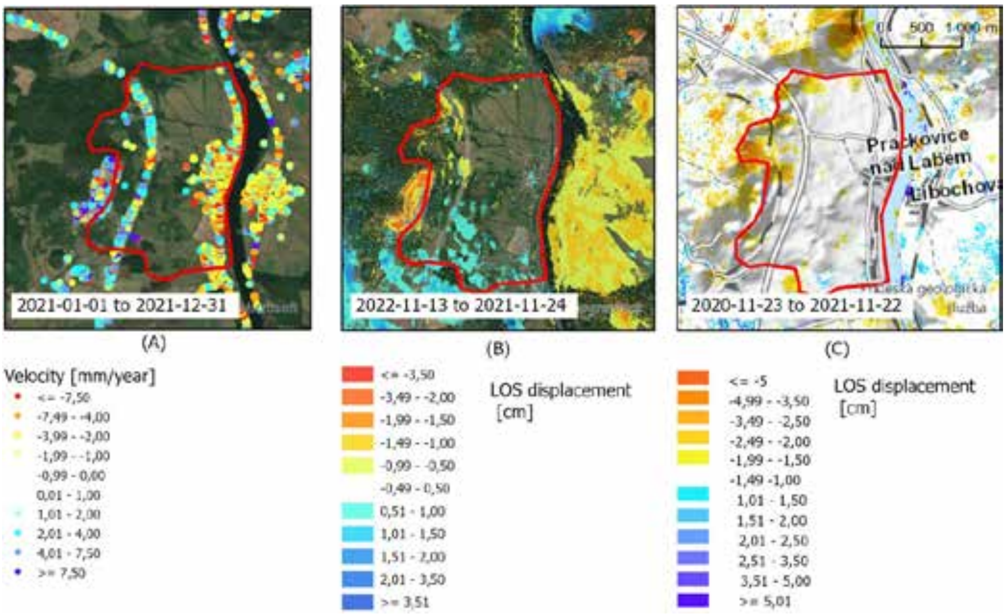

Fig. 1: Displacement detected by the means of radar interferometry in the surroundings of Dobkovičky using: A) PSI on Sentinel-1 data, B) DInSAR on TerraSAR-X data, C) DInSAR on ALOS-2 data.

Conclusions: The simultaneous utilization of different radar bands (C, X and L) has shown good potential in obtaining complex and spatially robust information, usually hidden using individual bands. Each of the data types has some advantages and disadvantages which on the other hand complement each other. The shorter wavelength (X-band) proved to be useful for man-made or bare soil targets, i.e. highway body or quarry. L-band data, on the other hand, showed high potential in usually uncoherent surfaces (i.e. forests) compared to the shorter wavelength radar data. C-band Sentinel-1 data form compromise between L- and X-band, however excels in its high availability and thus can be easily used in advanced DInSAR methods. We can conclude that the evaluated combination of radar data has a great potential for further upscaling to larger scale monitoring, i.e. to whole studied Elbe valley.

P2.5

SMART BOULDERS FOR MONITORING LANDSLIDES - A CASE STUDY FROM NEPAL

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Purpose: Rock falls and boulder falls can pose a significant hazard to people and infrastructure (Figure 1), however, limited methods have been used to monitor these boulders in the landscape and develop improved modelling approaches. Nor has the potential of using boulders to monitor larger landslides been routinely evaluated. This research evaluates the applicability of using boulder tags, equipped with GPS and accelerometers to monitor boulder and landslide movement. The study focuses on the Upper Bhotse Khose catchment, along the Ariniko Highway in Nepal, an area affected by landslides and floods triggered by monsoon rains and was impacted by the earthquake induced landslides following the Gorkha 2015 Earthquake

Fig. 1: Examples of the impact of boulder falls along the Ariniko Highway in Nepal.

Methods: Field mapping was undertaken to identify suitable field locations that satisfied 3 main criteria; firstly an active landslide to monitor with history of recent movement; secondly boulders within different geomorphological settings to tag and finally; a suitable location to install a gateway to record and transmit readings. Figure 2 shows the location of the gateway with a view to the landslides chosen for monitoring. 23 Tracker tags were installed over a period of 3 weeks to monitor the subsequent monsoon period in a range of geomorphological settings within the main landslide body and two adjacent drainage lines. In addition to the tags, additional rainfall monitoring and motion cameras were installed to validate movement.

Fig. 2: View from gateway looking towards landslide and drainage lines monitored with tags

Results: Out of the 23 tags installed, 9 indicated movement over the monsoon period. The majority of these 9 were located within the main landslide body, with small movement recorded indicative of minor reactivation of the landslide body. Three tags within the drainage lines showed sharper changes in movement, showing a greater level of activity within the drainage lines, potentially picking up fluvial processes rather than purely mass movement events. Utilising data from the motion camera, some boulder locations and movement was able to be validated.

Conclusion: The findings from this study identify that using boulder trackers/tags installed with GPS and accelerometers has the potential to be utilised to monitor boulder movement, validate boulder and rock fall modelling and monitor the movement of landslides. The methodology could potentially identify movement in real-time and thus form part of an early warning system. However, several limitations exist including line of site issues with the Gateway, duration of battery life in the tags and validating/constraining movements. Further develop is required and ongoing to enhance the system to improve these limitations

Fig. 3: (a) Gateway installed at the location of Fig. 2 (b) Boulder tag/tracker (c) example of boulder in landscape selected for monitoring landslide (d) Installed tag in boulder.

P2.6
COMPLEX SLOPE DEFORMATION AND DISPLACEMENT PATTERNS IN A FJORD SETTING (VESTLAND COUNTY, NORWAY)

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The large and complex rock-slope instability at Stampa lies in the direct vicinity of the touristic village Flåm above Aurlandsfjorden and a highly frequented road connecting the area with both Bergen and Oslo. Stampa has been mapped and sporadically monitored since 2005, and its maximum volume is estimated to be up to 800 Mm^3. While a failure of the entire slope is unlikely, several rock sections along the slope-plateau transition show significant displacement, including two sections that are monitored continuously by the Norwegian Water Resources and Energy Directorate (NVE). A small but very unstable part is a ca. 5,000 m3 large rock column, hereafter called «Block 4A», that rests on a highly fractured base, adding to a total volume of up to 40,000 m^3. Below Block 4A and the rock cliff it is attached to, a scree slope characterized by boulders up to ca. 500 m^3 large is evidence of a long rockfall and rock-slope failure history.

Since 2019, we have developed a monitoring system that continuously provides a comprehensive overview over the active deformation of the entire slope, ranging from 1) open bedrock fractures on the plateau, 2) over Block 4A and 3) down to the fjord. This includes a total station with 20 measure points, a tiltmeter, an extensometer, seismic sensors, a borehole equipped with a deformation cable and pore pressure sensors at the foot of the slope, as well as temperature loggers, radon films and sensors and anemometers at fracture vents on the plateau. This supplements a setup from NVE including ground based InSAR and corner reflectors for satellite based InSAR. Sporadic drone surveys give additional insights into natural ventilation systems through open bedrock fractures.

Preliminary data of most instruments show a seasonal variability and thus a correlation to changes in air temperature and precipitation: 1) The direction and velocity of air flow through open bedrock fractures is closely related to air temperatures aboveground. But the pattern and distribution of these natural ventilation systems is complex and still not completely understood, 2) Displacement rates of Block 4A is mainly controlled by ground temperatures and water infiltration. During the summer and autumn 2022 displacement rates reached up to 1.5 cm d-1 and the yearly total increased significantly from 10 to 60-70 cm. When ground temperatures are below 0°C, no significant displacement is registered at Block 4A. 3) The scree deposits below are less sensitive to seasonal variations and react with a larger time lag to high water availability. The scree is characterized by a creeping movement with 2-6 cm a-1 and decreasing velocities towards the fjord.

Stampa is a complex unstable rock slope, with different types of instabilities within a larger system. Displacement of small, almost decoupled instabilities, such as Block 4A are closely linked to ground temperatures and water availability. But further studies, including continued monitoring of the natural ventilation systems, are necessary to comprehensively decipher deformation patterns and the main deformation controls within the large unstable rock slope.

P2.7

MULTIDISCIPLINARY MONITORING OF ACTIVE LANDSLIDE - CASE STUDY OF RUSKA NOVA VES LANDSLIDE, EASTERN SLOVAKIA

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Purpose: This contribution deals with a multidisciplinary approach to the monitoring of landslide area in Ruská Nová Ves (Eastern Slovakia) (Figure 1). In order to clarify the characteristics of the slope movements the classical geotechnical methods were compared with modern remote sensing methods, electrical resistivity method and electromagnetic method. Namely borehole inclinometric measurements were matched against PS InSAR and shallow geophysical methods- Electrical Resistivity Tomography (ERT) and Electro Magnetic Radiation Method (EMR) and helped obtaining of realistic and actual character amplitude and orientation of the landslide mass movements as well as geometry and depth of the deformation zone.

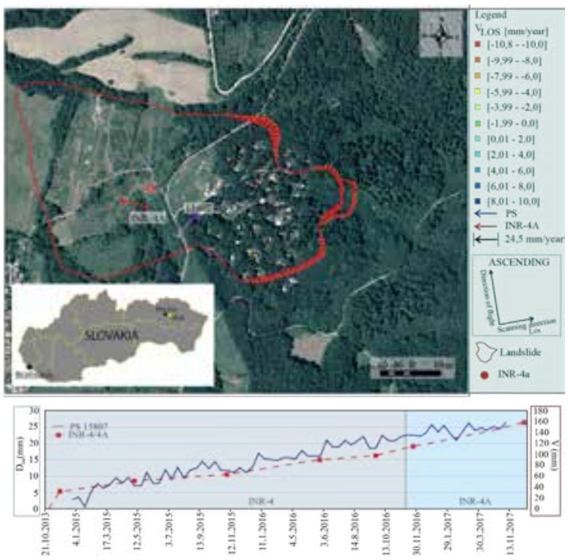

Fig. 1: Area of interest (AOI) map showing PS at the Ruská Nová Ves landslide (above) and displacement plot of DLOS (mm) and V (mm) compared to inclinometric measurements on borehole INR4/INR4A (below).

Methods: The assessment of landslide activity monitoring by using PS was based on the movements speed obtained from the image processing of Sentinel-1A satellite radar data in the direction of VLOS satellite scanning, from which the speeds of landslide movements in the direction of KSLOPE were calculated. Electromagnetic radiation occurs in landslides and usually is associated with the mechanical stresses and friction resulting from the displacement of the landslide layers due to sliding forces. Monitoring of EMR was carried out on boreholes by repetitive measurements of borehole profiles.

Results: In the case of Ruská Nová Ves landslide, there are significant movements, which were confirmed by the speed of VSLOPE 24.5 mm/year from the INR-4A borehole, which was relatively well approximated by the recalculated speed in the direction of KSLOPE from the PS with a value of -23.25 mm/year (Figure1). Based on the data from the inclinometers it can be concluded that the landslide in Ruska Nova Ves shows significant activity based on the average and median values in the direction of VLOS satellite scanning and in the direction of KSLOPE. Our results show that the largest differential deformations in the INR-4 borehole were recorded in the period from November 2015 to May 2016, together with the highest total EMR values registered in this time period. The minimum deformations found from inclinometric measurements are in good correlation with the minimum values of the EMR field (Figure2). Different values of the total EMR intensity in individual boreholes indicate changes in the spatial distribution of deformation stresses in the slope deformation body.

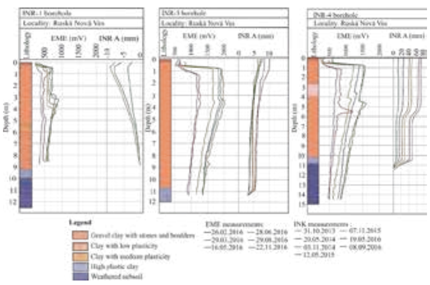

Fig. 2: Results of EMR method and its composition to inclinometric measurements on INR-1, INR-3 and INR-4 boreholes.

Conclusions: Based on results it can be stated that landslide in Ruská Nová Ves is a typical planar landslide with polygonal shear surfaces. Its lithology and geometry have been determined by ERT method and verified by boreholes situated in the landslide body. Two deformation zones were determined from inclinometric measurements from INR-4 and INR-4a boreholes, at the levels of 6-7 m and 11-12 m below the surface with an average displacement speed of 25.0 mm/year for a level of 0-6 m below the ground and 18.0 mm/year for level 6-11m below the ground level and azimuth 275°.

P2.8

ANALYSIS OF LANDSLIDE KINEMATICS THROUGH SATELLITE INTERFEROMETRY: A CASE STUDY OF THE MENDATICA LANDSLIDE, WESTERN LIGURIA, ITALY

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Purpose: Landslides are one of the most significant geologic hazards in Italy. A large relict landslide situated in the Ligurian Alps (Liguria, Imperia Province, north-western Italy), in correspondence of the Mendatica village, shows a complex residual kinematic, particularly after severe or prolonged rainfall events. To investigate the temporal evolution of the landslide state of activity since '90s, Interferometric Synthetic Aperture Radar (InSAR) data were used. In fact, datasets from the ERS-1/2, ENVISAT and Sentinel-1 satellites were analyzed to monitor displacements on a wide time frame in three relevant parts of the active landslide portion: head, body, and toe. As a further verification, data from geotechnical monitoring instruments (i.e., inclinometers) were used to validate the results obtained by satellite data.

Methods: The satellite data both in ascending and descending orbits permitted a time series analysis for investigating the geomorphological evolution of the area from 1992 to the end of 2021. The dataset from ERS-1/2 and ENVISAT, covering the period of 1992-2000 and 2002-2010 respectively, were processed by the Persistent Scatterers Interferometry SAR (PSInSAR) technique. The European Ground Motion Service (EGMS), making available the Sentinel-1 processed data over the whole European Community, allowed extending the investigation from February 2015 until December 2021. All the involved products derive from satellite radar images acquired by medium-resolution C-band sensors. The satellite measurements were validated by a comparison with the displacement data acquired by 15 inclinometers installed within the landslide body and activated at different periods since 2006.

Results: The analyses were conducted investigating the Persistent Scatterer (PS) data located on the head, the body, and the toe of the landslide to discriminate different behaviors for each sector. To make a solid time series analysis, PS data with high coherence were selected for all satellites. In the landslide head area, the time series in ascending geometry shows a linear displacement over time, while in descending geometry data is mainly noisy, but confirms the general movement. A major displacement is registered in the landslide body for both orbits, showing a linear trend from 1992 to 2010, and confirmed by extensive damage on buildings. For what concerns the landslide toe, it is not registered a relevant deformation, the time series appears noisy and PS data are less due to the vegetation and scarce anthropic elements. Moreover, PS data both in ascending and descending geometry are limited within the analyzed area. Comparing the obtained results with the inclinometer data, it was possible to observe a certain correspondence in terms of deformation.

Conclusions: The results of this study confirm the effectiveness of the InSAR techniques for the detection and monitoring of slope deformation, which can be combined with other technologies and in situ instruments for a detailed investigation. Thanks to the periodic updating of Sentinel-1 data from EGMS, this technique gives the opportunity to have a continuous control of landslides for future analyses and could allow the detection and investigation of other ground deformation in unknown moving and remote areas.

P2.9

LANDSLIDE MONITORING IN THE TOWN OF SEYÐISFJÖRÐUR IN THE AFTERMATH OF THE DESTRUCTIVE LANDSLIDE CYCLE IN 2020

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Purpose: A part of the settlement in Seyðisfjörður in East Iceland is endangered by landslides that have caused deaths, accidents, and extensive material damage through the centuries. In December 2020 after almost ten days of intense rainfall and snowmelt, several landslides hit the southernmost part of the town. The largest landslide occurred on the 18th of December and destroyed thirteen buildings and caused massive destruction. Alert phase was declared on December 15th and many houses in town were evacuated that day and in the days leading up to the biggest event. However, a part of the area where the largest landslide occurred had not been fully evacuated and a few people barely escaped. To reduce the risk of landslides in Seyðisfjörður a comprehensive system of monitoring devices was installed in the slopes above the town. The main aim of the system is early detections of instability that may lead to major landslides in the future.

Methods: The surface displacement in the slope has been sporadically measured for the past twenty years but in the aftermath of the landslide cycle the monitoring system was put in place. The system is composed of subsurface, surface, and remote sensing instruments, which includes a Total Station along with a network of prisms, Ground Based InSAR (GBRI), Shape Arrays (SAA), webcams, a few weather stations and one in the source area that measures air temperature, precipitation, soil temperature and moisture. Several piezometers were also installed in existing boreholes.

Results: The data from the monitoring system along with almost twenty years of surface displacement measurements have given us valuable information about the short- and long-term deformation of the slope and help us define the critical thresholds to operate the early warning system for the area.

Conclusions: The system has now been in operation for two years and during that time we have had two heavy precipitation events, in the fall of 2020 and 2021, where the system has come in good use both with gathering data for further research and as a method of constructing data for decision making.

P2.10

APPLYING LORA TECHNOLOGY ON A WIDE-STREAM MONITORING FOR LANDSLIDE

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Purpose: The ability of monitoring system to effectively transmit the signals to the server during slope disasters is a key issue in disaster prevention technology. However, due to the limitation of vast area, power supply and base station installation, the function of long-range low-power wide area network is more important and must be verified in slope areas.

Methods: From 2018, the research team conducted tests and verifications on LoRa transmit technology and discovered the effects of weather, vegetation, and terrain. LoRa modules with high performance, stability, and lower power consumption were used to test between Shenmu Village and Zhushan apron (spacing distance about 5 km), and the height and angle of the antenna were also evaluated to be more favorable for transmission. In addition, the test results using NB-IoT were not good herein.

Results: The performance of LoRa to transmit the data monitored on rainfall, crack, tilting, is proof to be well during each conditions of weather.

Conclusions: The technology of LoRa now is suitable to used in such areas without power-supply and telecommunications.

P2.11

STRUCTURAL EFFECT OF GEOLOGICAL SETTING ON SLOW-MOVING LANDSLIDE DISPLACEMENT PATTERN

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Purpose: Understanding landslide displacements in time and space is crucial in predicting and assessing these hazards. Although their general behavior is defined by the downslope movement, the rate and speed of the occurring deformations are influenced by many contributing factors, including structural features such as folds, faults, and discontinuities. However, they are mostly omitted to the detriment of the meteorological and hydrogeological factors. In our study, we aim to depict the contribution of faults and fold structures to slope destabilization and how they control landslide dynamics. Hence, we identified a relevant study case, the Prezzo landslide in the Italian Dolomites, which is a slow-moving landslide that requires permanent maintenance and whose sliding mechanism has a fold-related component.

Methods: We use the Multi-temporal Differential SAR Interferometry (MTI) techniques and in-situ measurements (GPS, inclinometers, piezometers) to analyze the Prezzo landslide dynamics and assess the slope behavior in time and space. The MTI techniques can provide information about the process's spatial extent and temporal trend. Firstly, we used the interferometric SAR products the European Ground Motion Service (EGMS) provides to have an initial idea about the occurring surface displacements. For a better slope assessment and updated velocities and displacement rates (post-2021), we processed the SAR images with the Small Baseline Subset (SBAS) technique, whose results provide a better spatial extent of the affected area.

Results: Preliminary results point out the active landslide sectors. EGMS products show mean displacement velocities of up to 7 mm/year in the ascending orbit and -8 mm/year in the descending one. What interests us are the much higher velocities in the fold's axial part compared to the flanks, which are also indicated and confirmed by the vertical component of displacements. Further on, we compare the InSAR results with respect to the in-situ data from GPS measurements, inclinometers, and piezometers and try to depict the influence of the syncline structure on the displacement pattern compared to the meteorological and hydrogeological factors.

Conclusions: The first results validate the need for such studies to be carried on and argue the use of Mt-InSAR results to assess the slope deformations spatially, which also allows a better evaluation of the contributing effect of the structural features. In mountainous areas, fault-fold structures play a significant role in the slope instabilities that threaten communities, requiring detailed investigations to minimize the risk they pose. In this regard, we intend to run numerical simulations, constrained by the InSAR results and in situ data, to understand the role of triggering factors and the effect of rainfall events.

P2.12
RAPID SAR-BASED LANDSLIDE DETECTION AND MAPPING

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Purpose: Rainfall-induced, abrupt landslides pose a major threat to society worldwide. In contrast to deep-seated slope instabilities where the ultimate mass release can be quite well-predicted based on accelerating surface movements, the exact location and timing of the triggering of shallow(er) landslide is hard to foresee. In order to validate and calibrate landslide early warning systems, knowledge of historic landslide events is crucial.

Methods: Here we evaluate the feasibility of exploiting C-band SAR data from the Copernicus Sentinel-1 satellite within Google Earth Engine for the rapid detection and mapping of landslides in multiple landslide events. SAR data is applicable regardless of weather and light conditions. The Sentinel-1 provides freely available and easily accessible SAR data with a spatial resolution of 10 × 10 m, a large areal coverage of 250 × 150 km and a repeat time of minimum 12 days per orbit. Preliminary tests were carried out for a selection of rainfall- or earthquake-triggered multiple landslide events available through the HR-GLDD Global Landslide Dataset (Meena et al. 2023). Multi-temporal change detection is used to generate enriched colour composites, which display changes in backscatter as Red-Green-Blue (RGB) composites. In these RGB composite landslides are visible in green, sometimes in purple (Lindsay et al. 2023). To generate the composites, data from six, two or one months from before and after the landslide events were used, with the length for the chosen interval dependent on image abundancy. The results of this approach are validated by manual expert mapping.

Results: Landslides can be identified in the pure backscatter data, but even better when using the above-mentioned change-detection approach. Landslides can then be automatically retrieved by calculating the ratio between two different scenes and further segmenting steps. The final automatically retrieved landslides outlines can be overlaid on conventional maps, or other satellite imagery, and crucial geometric parameters such as location, height, exposure of release area, length of runout, can be fed into pre-existing landslide inventories. Our preliminary results indicate that landslides are detectable to a high degree, when looking at all case studies together. Detection rates for the individual case study sites vary, however, with detection rates increasing with increasing landslide size and depending on initial surface conditions. We also found that landslides need to exceed a size of approximately 200–300 m2 in order to be reliably detectable in Sentinel-1 data (Lindsay et al. 2022).

Conclusions: Automatic, rapid landslide mapping exploiting Copernicus Sentinel-1 satellite available in Google Earth Engine was tested for several case study sites. Our preliminary results suggest that GEE is a feasible tool for the rapid detection and mapping of landslides in multiple landslide events, but that landslides need to be of a certain minimum size to be detectable and that local site conditions (such as pre-event vegetation type) is influencing the detection rate.

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P2.13

MONITORING AND EARLY WARNING OF LANDSLIDES IN THE PHILIPPINES: A CASE STUDY OF RAINFALL-TRIGGERED LANDSLIDES IN ILOILO PROVINCE DURING 2022 SEVERE TROPICAL STORM NALGAE

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Purpose: The Philippines, by virtue of its geographic circumstance, is highly prone to landslides. In the past two decades alone, thousands of lives were lost, and billions of Philippine pesos' worth of properties were damaged due to landslides. Most of these landslides were preceded by heavy or continuous rainfall, and no prior monitoring and early warning were in place. These highlight the need for a monitoring and early warning system for communities at risk of landslides. A research program, Dynaslope Project under the Department of Science and Technology – Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS), was conceived to develop a means for monitoring landslides that is cost-effective yet accurate, efficient, and reliable. The program has developed, deployed, and implemented an early warning system for deep-seated landslides (EWS-L) through sensor technology and community participation.

Methods: Three concurrent landslide events in October–November 2022 in Iloilo Province — triggered by rainfalls from Severe Tropical Storm Nalgae — provided an opportunity to demonstrate our monitoring strategies and assess the implementation of the EWS-L in a real-world setting. The development of three deep-seated landslides in Iloilo, to wit, at Boloc village in Tubungan, Inabasan village in Maasin, and Marirong village in Leon, were investigated based on real-time monitoring data. Ground-based monitoring instruments that include subsurface tilt sensors and rain gauges collect data round-the-clock through a data logger, which sends it to a central server. In addition to instrumentation, the at-risk community also regularly monitors surface ground movement through stakes and observation of manifestations of surface features. Processed data from continuous and real-time landslide monitoring undergoes analysis and interpretation before being disseminated as early warning information to the community at risk.

Results: While the exact date and time of a landslide are difficult to predict, we can anticipate it within days or even hours by monitoring potential triggering conditions such as rainfall or the progress of ground movement. In the October–November 2022 landslide activities, peak one-day (~130 mm) and three-day rainfalls (~250 mm) came at least six hours before critical ground movements were detected and observed. These rainfall depths amount to 50.8% and 97.7%, respectively, of the normal monthly rainfall (256 mm) in Iloilo in October. In other words, a month-worth of rain was poured in three days to trigger critical ground movements. The ~130 mm one-day rainfall and ~250 mm three-day rainfall may serve as thresholds for landslide advisories in the three sites.

Conclusions: Critical ground movements observed necessitate the issuance of the highest landslide alert level, which indicates that slope failure may be imminent and that the households at risk must evacuate. While a major landslide did not eventually happen, households within the identified hazard zones were successfully evacuated; these affirm that the above monitoring and early warning activities represent some degree of success. Nevertheless, the continuing activity of the landslides and the likely occurrence of rainfall triggers suggest that the complete failure of the slopes is bound to happen in the future, proving that the EWS-L is even more necessary.

P2.14

DETERMINATION OF LANDSLIDE KINEMATICS BASED ON UAV PHOTOGRAMMETRY WITH NATURAL FIELD DETAILS

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Purpose: The purpose of this study was to determine the complex kinematics of a landslide based on UAV photogrammetry that provides optical images and elevation data (NMT). Comparison of data from acquisitions at different times allowed detection and quantification of the changes occurring on the landslide surface.

Methods: The study was conducted on the Kasinka Mala debris flow located in the Polish part of the Carpathian Mountains. The landslide poses a serious threat to buildings located in a short distance from the edge of the main slope. The bedrock consists of flysh sediments consisting of thin-bedded sandstone and chert shale. Since 2017, 9 photogrammetric acquisitions have been carried out. The obtained orthomosaics were used to measure the coordinates of characteristic objects present on the ground surface (boulders, tree branches etc.). Based on the change in their position, horizontal displacement vectors were determined. The displacement map was then combined using the natural neighborhood method. DTMs were made from each photogrammetric data set representing certain temporal stage. Therefore, in order to calculate vertical displacements the differential models were generated.

Results: Differential displacement kinematics were combined from analyses at 8 time intervals. During this time, the extent of the landslide did not change significantly, but large changes occurred on the surface of the landslide. In the zone of the main scarp, displacement in the vertical profile played a greater role with respect to small horizontal displacements. However, this scheme turned around in the middle zone of the landslide (trough) where horizontal component increased of up to 16 m/year and vertical component decreased respectively. In the lower (terminal) part of the landslide, small horizontal displacements and small vertical displacements were found.

Conclusions: The Kasinka Mala landslide is in constant motion, influenced by groundwater outflows in the upper part of the landslide and fluvial erosion of the front. The azimuth of horizontal displacement is disturbed due to the presence of immobile packets of coarse sandstone in the middle part of the landslide. The measurement method of the use of characteristic objects present on the ground surface works best for slow displacements that do not mix colluvium on the surface. Based on them, the direction and magnitude of the landslide can be traced. For some objects, it was possible to determine cumulative displacements over several years.

P2.15

APPLICATION OF STATISTICAL CLUSTERING TECHNIQUE TO DIAGNOSE SUB-ZONE ACTIVITIES IN POTENTIAL DEEP-SEATED LANDSLIDE SITES

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Multi-Temporal Interferometric Synthetic Radar (MT-InSAR) is a remote sensing technology which has been increasingly applied to construct temporal evolution of surface deformation. In the technology, a sequence of radar interferrograms are analyzed such that a high density set of time coherent points (TCP) are often identified. On these TCPs, the line-of-sight (LOS) deformation are computed and, as a result, high accuracy and wide coverage of the transient surface deformation are generated. In Taiwan, the MT-InSAR technology has been applied to long-term monitoring of slope activities of potential deep-seated landslides, Chen & Kuo (2022). In this presentation, the D062 potential deep-seated landslide site, located in Nantou County, about the center of Taiwan, is taken as an example, Figure 1(a,b). Its area is about 60.7 ha and the slope direction is towards the west at about 29.2. The positions of the data points and the averaged deformation rates on the points are shown in Figure 1(c). These data are based on the image sequence between the 2014~2022 by the ALOS2 satellite, JASA.

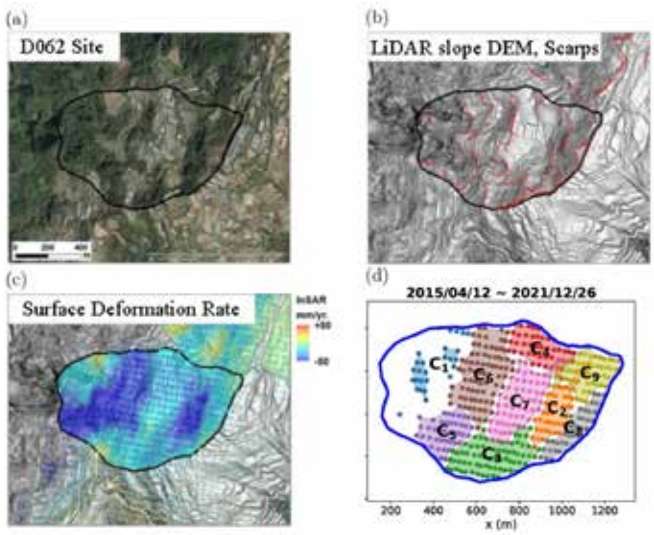

Fig. 1: a) Aerial photo of D062 potential deep-seated landslide site, Nation County Tiwan; b) LiDAR slope DEM and identified surface scarps; c) Averaged surface deformation rate between 2015 and 2021, based on ALOS2 satellite images; d) Reference clusters of the surface deformation rate.

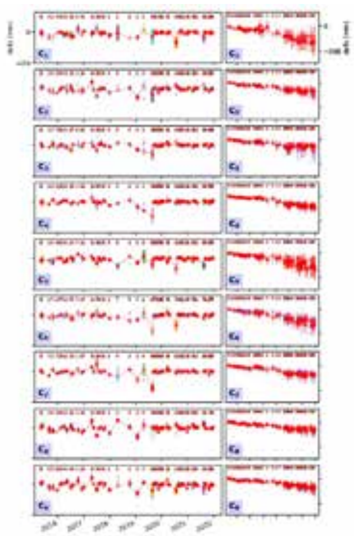

Fig. 2: Time sequences of the representative incremental deformation (left column) and accumulated deformation (right) of the associated clusters.The light blue shadowed clusters are the reference clusters in figure 1 (d). The incremental deformations share the same scale and so do the accumulated deformations.

Inspections of the MT-InSAR data over many potential deep-seated landslide sites (> 150) reveal that the surface deformation patterns somewhat visually correlate to the distribution of the fracture scarps in the sites, e.g. 1(b,c). This characteristics is a call for a new set of objective analytical methods to assist the diagnose of the properties of the potential landslide sites. In this study, a Gaussian mixture model are proposed to perform statistical clustering for the surface deformation data points, McLachlan & Basford (1988). The long term averaged deformation rate data are clustered to generate a referenced cluster set, Figure 1(d). Then, the clustering technique isapplied sequentially to the incremental deformation data within the MT-InSAR sampling period and associated clusters referenced to the reference cluster set are defined to connect multi-temporal deformation clusters. The time series of the representative incremental and accumulated cluster deformations, hence, can be composed. The example deformation time series are as shown in Figure 2. It is clearly seen from the accumulated deformations that the all clusters deform in the downslope direction while the clusters closer to the slope foot, e.g. C1, C5, C6, have generally larger deformations, while the clusters closer to the top have smaller deformations. On this observation, we summarize that the activity of the slope can be classified as a rock slide, Varnes (1978), and the lower parts of the slope have higher activities. Further applications on other potential deep-seated landslides reveal that the clustering technique could enable investigations on the relations among the time series of the deformation clusters, precipitations or other influential factors of the landslide activities.

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P2.16
SUBSURFACE FRACTURE VENTILATION AND GAS EMISSION AND THEIR RELATION TO ROCK SLOPE DEFORMATION

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The large and complex rock-slope instability at Stampa is located above Aurlandsfjorden and near the tourist town of Flåm in Western Norway. A highly frequented road connecting the area with both Bergen and Oslo, runs along the foot of the slope. The unstable rock slope includes several potential failure scenarios that could lead to economic and societal consequences for the area. A steep rock cliff separates the mountain plateau from extensive scree deposits below. The bedrock above the cliff hosts open fractures mostly running parallel or perpendicular to the slope. This fracture network influences the subsurface bedrock temperature field due to air ventilation and water infiltration, which in turn can have an influence on the slope stability. Ascending air flow through fracture networks, the so-called chimney effect can lead to the cooling of the ground. This effect is often observed in coarse blocky scree slopes and may be intensified through the occurrence of extra-zonal permafrost. In addition, natural ventilation through open fractures can lead to the exhalation of natural gases such as radon (222Rn) and thoron (220Rn). Radon, with its half-life time of 3.8 days, has been used to characterize bedrock fracture networks. Radon concentration in subsurface fractures is influenced by the air flow rate, rock type and the exposed rock surface, which depends on the presence of ice and the ground water level.

In order to monitor air flow intensity and direction, we have installed anemometers in two bedrock fractures. In addition, through field mapping and drone surveys with optical and thermal sensors, we have identified natural vents where relatively warm air flows out in winter. Radon concentration at selected vents is continuously monitored by radon films and sensors to verify ventilation patterns and to study the connection and interplay between individual ventilation systems.

Preliminary results show that the direction of the air flow changes when surface air temperatures transition into sub-zero degrees, and vice versa. Some of the vents at the slope plateau represent the upper part of an underground fracture ventilation system, whereas others represent the lower part of such a system. This is determined by the direction of the air flow at the vents since the chimney effect is characterised by relatively warm ascending air during winter and a cooling descending air flow during summer. First results from an early test study with short term radon monitoring using radon films show that radon concentrations are varying with values exceeding 4000 Bq/m^3 at some vents. Generally, radon measurements support observed air flow patterns.

The ventilation through open bedrock fractures at Stampa is complex and still not completely understood yet. The ventilation pattern depends on various atmospheric conditions such as air temperature, wind, air pressure and the location of the fracture. Changes in climatic and meteorological parameters lead to thawing of potential extra-zonal permafrost, which can have implications on slope stability. Insights into the thermal condition within the ground and slope deformation can be gained by continuing monitoring of the natural ventilation system and gas emissions.

P2.17
UNDERSTANDING AND RECONSTRUCTION OF THE EVOLUTION PROCESS OF THE SLOW-MOVING LANDSLIDES IN STEEP CANYON

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Purpose: As an important part of geomorphic unit in high mountain area, Steep Canyon is one of the areas where slow-moving Landslide occur most frequently and with the largest scale due to its complex geological setting, steep terrain and intense river erosion, which pose serious risks to infrastructure and people downstream. We focus here on the slow-moving landslides along Jinshajiang steep canyon in the Southeast Tibet of China to revel the scientific issues what factor control the evolution process of these landslide.

Methods: We first estimate the ground displacement from time series analysis of Landsat series images and Sentinel-1 SAR images, spanning a more than 10 year period. Then field surveys on typical landslides were carried out, including reconstructing their three-dimensional structure, obtaining their material composition and rock mass structure and crevices information.

Results: The results show that there are significant differences in the deformation velocity of slow-moving landslides in the steep canyon. Specifically, the fastest landslide deformation velocity reaches 67 meters per year, so that this change can only be reversed by the correlation analysis on optical image. On the contrary, the slowest landslide deformation velocity is less than 1 meter per year, and this deformation can usually only be retrieved by time-series SAR technology.

Conclusions: Combined with the field investigation and data analysis of meteorological stations and hydrological stations, we found an interesting phenomenon that the factors affecting the accelerated deformation of landslides are determined by the material and structure of the landslide. Accelerated deformation of high-level bedrock landslide have an obvious response to rainfall infiltration damage, but accelerated deformation response of loose accumulation landslide and ancient landslide is resulted from to river peak discharge. These observations provide a basis for us to build a regional landslide dynamic prediction model in steep canyon that pave the way of dynamic risk management of slow-moving landslide.

P2.18
RETRIEVING TWO-DIMENSIONAL KINEMATICS OF LANDSLIDES IN TENA VALLEY USING ASCENDING AND DESCENDING SENTINEL-1 DATASETS

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Purpose:
1. To detect the active landslides in Upper Tena Valley, Central Spanish Pyrenees using ascending and descending Sentinel-1 datasets
2. To suppress the spatial-temporal decorrelation caused by dense vegetation or snow cover and invert the two-dimensional deformation of the typical landsides in Tena Valley.
3. To explore the relationship between seasonal factors and landslides deformation.

Methods:
1. Merging the knowledge of Distribute scatterers and intermittent point targets to calculate the deformation rate map with high density.
2. Retrieve the two-dimensional deformation time series of typical landslides from ascending and descending Sentinel-1 datasets.
3. Extract the seasonal factors by singular spectrum analysis and relevant prior knowledge.

Results:
1. The active landslides in Tena Valleys are detected and compared by combining deformation maps, optical images and related researches.
2. The two-dimensional deformation time series of typical landslides are subsequently retrieved.
3. The effect of seasonal precipitation and melting on slope deformation are analyzed.

Conclusions: The results evidence that the technical routine proposed in this paper cannot only be used to derive the different kinematic process of earth-flow and deep-seated landslides in Tena valley, but also to provide an insight into the relationship between acceleration of surface deformation and seasonal effects.

P2.19

INTEGRATED GROUNDWATER AND SLOPE MOVEMENTS MONITORING FOR THE CHARACTERIZATION OF COMPLEX HYDROGEOLOICAL PROCESSES IN DEEP-SEATED LANDSLIDES: AN EXAMPLE IN THE NORTHERN APENNINES (ITALY)

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Purpose: Large-scale and deep-seated landslides are complex hydrogeological systems, in which multiple aquifers might coexist and play different roles in determining slope instability. The Ca' Lita earthslide-earthflow in the Northern Apennines (Italy) has been recognized as such by previous works, with a confined aquifer below the main slide surface and a phreatic one hosted in the sliding mass. This landslide, after a major reactivation in 2004 and an extensive deep-drainage project, has once again resumed activity in March 2016 and February 2019, when roto-translational sliding took place 40m in depth determining up to 30m displacement.

Methods: From October 2018 to July 2019, an integrated monitoring system consisting of a multi-parametric probe installed in a drainage well, groundwater sampling and analysis and a continuous single frequency GNSS receiver, has been operated in order to compare and estimate variation in the groundwater conditions during landslide reactivation. Furthermore, by the analysis of multi-temporal Digital Elevation Models (DEM) derived by Uncrewed Aerial Vehicles (UAV) photogrammetry and Aerial transported Light Detection And Ranging (LiDaR) an estimation of displacements and volume changes have been achieved.

Results: Monitoring results, complemented with hydro-chemical analyses, show that the development of shear along the sliding surface determines a transition from confined to unconfined conditions on the lower aquifer, with a significant inflow of deep groundwater into the most surficial unconfined aquifer hosted in the sliding mass

Conclusions: These findings reveal the complexity of hydro-mechanical processes at the slope scale and can be used to valuate alternative risk mitigation options and set up early warning system.

P2.20

A SLOPE STABILITY ANALYSIS OF YUSUI STREAM IN SOUTHERN TAIWAN WITH MULIT-STAGE REMOTE SENSING DATA

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In August 2021, the torrential rain triggered a deep-seated landslide located in the upstream of Yusui Stream and an enormous amount of debris was brought to the downstream and crashed Minbaklu Bridge. Although the Directorate General of Highways (DGH) cleared the route and built a temporary steel bridge for people to pass through, this incident has highlighted the fact that the roads of the region can break when plum rain or torrential rain occurs. To investigate such circumstance, this study has adopted optical satellite imagery, aerial LiDAR and UAV, technologies that complement each other with their respective benefits and drawbacks. The airborne LiDAR derived DEM (digital elevation model) constructed based on the images collected between 2016 and 2022 can remove vegetation and present the real ground surface, enabling researchers to calculate the volume of landslide materials of Yusui Stream and Putanpunas Stream. The three-dimensional terrain interpretation and landslide volume calculation results, on the other hand, reveal that the landslide surface area has continuously increased over the last six years due to abundant rainfall brought by typhoons and torrential rain, causing an enormous volume of debris falling into the main river channel and piling up at its confluence with Laonong River.

In addition, this study has also adopted an aerial LiDAR derived DEM to effectively reflect topographic features of the landslide area. Nevertheless, the interpretation can be hard in areas with small-scale shallow landslides due to smaller changes to the surface elevation. Optical satellite imagery before and after the sliding is therefore required to quantify the change of landslide volume, helping to determine potential landslide and accumulation areas even more effectively. In regard to studies of mountain roads in the future, it is suggested that researchers can adopt multiple and multi-scale satellite and remote sensing data and continuously update orthophotos of optical satellite, aerial photography and UAV to facilitate the interpretation and delimitation of landslide areas and to further improve the accuracy and reliability of the results.

This study has been completed in accordance with work items specified in the Soil and Water Conservation Bureau (SWCB) project: First, aerial LiDAR derived DEM was used to calculate the volume of landslide materials of Yusui Stream and Putanpunas Stream and their respective volumes between 2016 and 2022 were 1.2x107m3 (at the depth of 80 m) and 2.9x107m3 (at the depth of 120 m). Second, radar satellite images, including 85 ALOS/ALOS-2 images, were collected and prepossessed for an InSAR analysis. The analysis results indicate that the annual average deformation of study sites can reach 380 pt./km^2 and, based on the time-series InSAR analysis data of 2020 and 2021; and that five landslide-prone slopes in the catchment areas of Yusui Stream and Putanpunas Stream have been identified. Third, by screening the long-term surface displacement with InSAR data of 2020 and 2021, a wide-scale landslide activity analysis has been carried out on the watershed and sub-catchments of Laonong River. The results indicate that the downward movements mainly occurred located along river channels and gullies, indicating that the high displacement activity of catchment and watershed areas is resulted from the evolution of the slope-river system.

P2.21

DEEP-SEATED LANDSLIDE ACTIVITY MONITORING OF COASTAL HIGHWAY IN EASTERN TAIWAN USING ADAPTIVE TIME-SERIES INSAR WITH INTEGRATING SENTINEL-1 AND REMOTE SENSING DATA

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Purpose: Route 9 is the most important provincial highway in Taiwan, linking the northern and southern counties. The potential deep-seated landslides have always been a hazard to highway safety. In order to introduce innovative remote sensing techniques to assess the activity of landslides and determine sliding hotspots, next-generation InSAR techniques, which are called adaptive time-series interferometric synthetic aperture radar combined with persistent scatterer and distributed scatterer were applied in this study.

Methods: This analysis uses conventional geotechnical monitoring data as the basis for a preliminary assessment of landslide masses in conjunction with high-precision LiDAR and UAV datasets. The airborne LiDAR DTMs equip the basis for deep-seated landslide micro-topography interpretation and mapping. The ground deformation analysis was carried out utilising ATS-InSAR combined with an artificial corner reflector along the coastline.

Results: InSAR and other remote sensing tools for assessing ground change have shown that potential landslides in the region are also slowly and constantly sliding phenomena, even in non-flood periods. The mean sliding velocity in this region is 30-38 mm/yr. The downward sliding velocity of the whole landslide body reveals a linear and stable trend. It is worth noting that the displacement trend of ATS-InSAR on a given sliding zone is almost identical to that of GNSS and inclinometer monitoring. The analysis result of the wet and dry seasons indicates that landslide behaviour on this slope is significantly influenced by groundwater, mainly during the typhoon season. The sliding depth (38 m) suggests that the sliding mechanism at this location is the debris slide along the surface of the bedrock. The usual water table height is almost at the same level as the sliding depth from the automatic monitoring system.

Conclusions: The wide-area ground deformation assessment through InSAR analysis can compensate for the lack of traditional monitoring points. Further overlaying the frequent aerial 3D terrain model by UAVs, InSAR analysis results can effectively identify the terrain change and activity of specific sliding blocks. Roadworks have improved this section, but InSAR analysis indicates that the potential for landslides will continue to cause new cracks in the retaining wall beyond 2021. In this study, we also attempted to integrate the results of InSAR analyses to update the influence of the landslide hotspot on the coastal corridor. For highway disaster prevention, ATS-InSAR provides long-term slope monitoring information and early warning of road subsidence caused by gully evolution and coastal erosion. Finally, the competent authority can employ the grid-based multi-temporal road variation assessment for regular highway maintenance and disaster prediction in advance.

P2.22

SEISMIC MONITORING OF KARST HYDROSTRUCTURES FOR GEOLOGICAL RISK MANAGEMENT: PRELIMINARY FINDINGS FROM LE CAPORE AND PESCHIERA SPRINGS IN THE CENTRAL APENNINES, ITALY

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Purpose: Aiming to non-invasive and passive monitoring of vulnerable structures to the geological risk, wave propagation-based methods are preferred. Generally, these methods are referred to as non-standard seismic techniques, the notable among them are the seismic ambient noise (single-station and array), emitted seismic and acoustic emission based. In recent years, these techniques have significantly evolved, especially in monitoring the various aspects of the natural risk environment using suitable sensor deployment schemes, hight-performance data processing algorithms and user-oriented results presentation strategies (i.e. early warning system). However, these methods are still evolving and require confirmations supported by multi-parametric monitoring sites. In this context, Le Capore and Peschiera springs, which are two karst hydrostructures of strategic importance for the roman water supply system (managed by ACEA ATO2, i.e. water utility), represent challenging case studies. In particular, the Peschiera spring has been instrumented, since two decades, through multi-parametric monitoring system to support a safe management of the local geological risk. For monitoring purposes, passive seismic techniques were applied on the prone-to-fall compartment using two different approaches

Methods: A time-continuous analysis of ambient noise levels induced by anthro-environmental factors, includes the computation of power spectral density (PSD), spectrograms and root mean square (RMS) energy at different frequencies. Subsequently, single-station techniques (i.e., horizontal-to-vertical noise ratio-HVNR and seismic ground motion polarization) have been adopted to detect time-lapse changes in the natural system conditions and/or properties. Moreover, local and felt seismicity was analyzed to detect sequential events of fracture hypogeous instabilities involving the karst aquifers, as they could anticipate or be linked to local crack generation or propagation in the rock masses. As it regards to the ambient noise measurements, the stationarity of the high-frequency peaks of the daily HVNR curves is investigated by multi-attribute peak-stationarity (i.e., amplitude, frequency, width and trough) and polarization evaluation criteria at Le Capore for detecting changes in Green's function. The seismic ambient noise displacements RMS and other relevant climatological factors are also compared with HVNR peak variations. These peak driven changes in S-wave are further utilized to constrain evidences collected from microseismic emissions. Additionally, the nanoseismic monitoring technique has been applied for the detection and localization of microseismic events.

Results: The seismic ambient noise RMS indicated a day-night variability in energies at the considered frequency ranges. Preliminary results showed significant variations in the HVNR peaks found positively correlated with the time-lapse variations, especially sensitive to the S-wave modifications possibly related to the rock slope deformation or changes in ambient noise levels.

Conclusions: At this stage of the study, it can be concluded that the aforementioned integrated seismic geophysical techniques can pave the way to develop an optimal management of the geological risk within Le Capore and Peschiera hydrostructures

P2.23
FIELD MONITORING AND KINEMATIC BEHAVIOR OF A MULTI-SLIDING ZONES LANDSLIDE IN THE THREE GORGES RESERVOIR AREA

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Purpose: Reservoir landslides pose the great threat to shipping safety, human lives and properties, and the operation of the hydropower station. Many large landslides may have multi-sliding zones that are simultaneously active due to the influence of engineering geological and hydrogeological conditions (Xu et al., 2022). Understanding the deformation characteristic and kinematic behavior of the multi-sliding zones landslide is very important to evaluate the stability and long-term safety of the landslide.

Methods: In this study, the deformation characteristics, influence factors and kinematic behavior of the Majiagou landslide in the Three Gorges reservoir area are revealed based on field investigations, multifield monitoring and the Apriori algorithm. The Majiagou landslide was initiated with three sliding zones when the first impoundment of the Three Gorges Reservoir. Since 2003, abundant data have been obtained from the Majiagou landslide about rainfall, water level, surface deformation and borehole inclinometers.

Results: Monitoring results show that the surface and deep deformation of the Majiagou landslide exhibits the step-type increase under the combined effect of reservoir water level and rainfall. The deep sliding zone is the main sliding zone, which has visible abrasion and polishing surface, and its clay mineral particles have obvious directional arrangement characteristics. The deep sliding zone have the largest relative displacement and velocity and enters the accelerated deformation stage about one month before the slope surface displacement. The distinction of surface and deep deformation behavior indicates that rainfall and water level fluctuation have different effects on the stability of the Majiagou landslide. Apriori algorithm shows that the main triggering factor for the relative movement of the deep sliding zone and the slope surface displacement is reservoir water level decline, the main triggering factor for the relative movement of the shallow sliding zone is the heavy rainfall.

Conclusions: These results comprehensively analyzed the kinematic behavior of the Majiagou landslide, which is of great significance for disaster prevention and treatment of analogous multi-sliding zones landslides.

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P2.24

UPDATING LANDSLIDES' INVENTORY MAPS IN MINING AREAS BY INTEGRATING INSAR WITH LIDAR DATASETS

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Purpose: Slope failures are typical active deformation processes that pose a significant hazard in current and abandoned mining areas given their considerable potential to produce damage and affect the population at large. In order to minimize the impact caused by the deformational processes in mining areas, much effort has been devoted in recent decades for the development of new approaches to obtain and update active deformation inventory maps with a particular focus on those approaches based on remote sensing.

Methods: This work illustrates the potential of exploiting space-borne InSAR and airborne LiDAR techniques, combined with data inferred through a simple slope stability geotechnical model, to obtain and update inventory maps of active deformations in mining areas. The proposed approach is illustrated by analyzing the region of Sierra de Cartagena-La Union (Murcia), a mountainous mining area in southeast Spain. Firstly, we processed Sentinel-1 InSAR imagery acquired both in ascending and descending orbits covering the period from October 2016 to November 2021. The obtained ascending and descending deformation velocities were then separately post-processed to semi-automatically generate two active deformation areas (ADA) maps. Subsequently, the PS-InSAR LOS displacements of the ascending and descending tracks were decomposed into vertical and east-west components. Complementarily, open-access and non-customized LiDAR data were used to analyze surface changes and movements. Furthermore, a slope stability safety factor (SF) map was obtained over the study area adopting a simple infinite slope stability model. Finally, the InSAR-derived maps, the LiDAR-derived map and the SF map were integrated to update a previously published landslides' inventory map and to perform a preliminary classification of the landslides and other active deformation areas with the support of optical images.

Results: A total of 28, 19, 5, and 12 ADAs were identified through ascending, descending, horizontal and vertical InSAR datasets, respectively, and 39 ADAs through LiDAR. The subsequent preliminary classification of the ADA allowed to identify 15 areas of landslides, 7 landslides overlapping with other phenomena, 34 areas with inactive landslides, 20 areas affected by other phenomena and 10 possible false positive ADAs.

Conclusions: The results highlight the effectiveness of these two remote sensing techniques (i.e., InSAR and LiDAR) in conjunction with simple geotechnical models and with the support of orthophotos to update inventory maps of active deformation areas in mining zones.

P2.25
AERIAL PHOTOGRAMMETRY AND INFRARED THERMOGRAPHY FOR THE NON-CONTACT CHARACTERIZATION OF ROCK MASSES

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Purpose: This study is focused on the combined use of RGB photogrammetry and infrared thermography (IRT) for the non-contact rock mass characterization, with the aim of finding a practical utility for the remote definition of the main geomechanical parameters in the qualitative and quantitative discontinuity sampling and description. This could provide a key practical utility either in the surveying of poorly accessible rock cliffs, or when non-contact measurements are required by specific restrictions, or in case of preliminary project stages with low financial availability for field surveys.

Methods: Aerial photogrammetric and IRT surveys were carried out at a test site characterized by metamorphic rock outcrops affected by a heavy degree of fracturing. The methodological approach can be divided into two branches: 1) reconstruction of a rock mass digital model based on photogrammetric outcomes; 2) definition of a thermal 3D rock mass model based on the acquired IR images. The photogrammetric data acquisition was carried out by using a quadricopter equipped with a digital sensor 1/2.4‘‘ CMOS (active-pixel sensor) and a correct georeferencing was ensured by the GPS localization of ground control points located within the study area. Based on acquired RGB images, a digital rock mass model was built and discontinuity data were extracted from the point cloud according to different algorithms. A comparison between digitally-derived data was performed, as well as a field data validation to ensure the reliability of achieved outcomes. On the other hand, IRT surveys were carried out by a 320x240-pixel thermal camera. Thermal images were post-processed and arranged to build a thermal dense point cloud looking for peculiar geomechanical features related to the most visible discontinuity sets.

Results: The analysis of RGB point clouds allowed gaining information on the geostructural setting of the rock masses through the extraction of the spatial orientations belonging to the main discontinuity sets. A good match between digitally-derived and field data was found. The analysis of IRT point clouds allowed identifying the main thermal anomalies characterizing the outcrop, which were related to the specific geomechanical setting. In particular, based on the thermal anomalies labeling the discontinuities, the Thermal-spacing (T-spacing) and the Thermal-Rock Quality Designation (T-RQD) were introduced as new pioneering parameters that can be evaluated when dealing with rock a mass thermal analysis (Mineo et al., 2022). Both parameters provide information related to the loosest rock mass volume, whose instability is driven by the most open and persistent discontinuities.

Conclusions: Achieved results demonstrate that this combined methodology is suitable for remote rock mass surveys based on the analysis of digital rock mass models. The use of thermal dense point clouds paves the way to the development of innovation in terms of digital technology applied to rock mass instability issues. In this regard, further studies are needed to test the applicability of such procedures on different rock masses and in different geological and environmental settings.

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P2.26

ANALYSING MULTI-TEMPORAL 3D POINT CLOUDS FROM A PERMANENT TERRESTRIAL LASER SCANNER: AN APPLICATION FOR SLOW-MOVING LANDSLIDES MONITORING

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Purpose: In recent years, high-resolution and multi-temporal techniques for 3D mapping have been rapidly developed. Landslide monitoring benefits from the increasing availability of 3D data time series, which allows geomorphometric analysis of surface changes at high spatio-temporal resolution. Especially slow movements ranging from millimeters to centimeters per year need long-term monitoring to better understand the complex mechanisms driving the landslide dynamics. The aim of this work is to present the integration of multi-temporal 3D point clouds from a permanent terrestrial laser scanner (p-TLS) as part of a long-term monitoring system that has been implemented in a complex, slow-moving landslide in Lower Austria (Austria) since 2015.

Methods: An autonomous p-TLS system is used to daily monitor the area of interest and the collected data are automatically sent to a remotely accessible server after an automated pre-check. The system consists of a long-range Optech ILRIS-3D laser scanner together with a laptop with a permanent power supply and internet connection. In this study, standard workflow steps have been applied for achieving comparable point cloud datasets: i) coarse and ICP (Iterative Closest Point) co-registration of the clouds; ii) transformation to georeferenced coordinates; iii) terrain filtering using existing algorithms, Cloth Simulation Filter (CSF) [1] in Cloud Compare and Simple Morphological Filter (SMRF) [2] with Open 3D, respectively. The results of the change detection analysis are obtained through the multiscale model-to-model cloud comparison (M3C2) algorithm [3].

Results: Early results are obtained by comparing the yearly dataset for the period from 2016 to 2023. They show a varying spatio-temporal pattern, in particular evidencing total displacements ranging from -0.85 m to -1 m in the central sector. For a comparison of the most effective processing, as well as to assess uncertainty levels, these findings will be further validated with additional monitoring systems, such as inclinometers and UAV surveys, that can complement their interpretation. Additionally, future analysis will consider comparisons to detect seasonal trends and assess the relationship with hydro-meteorological variables.

Conclusions: Although several methods are already available to monitor 3D displacements over time, the use of multi-temporal 3D point clouds from a p-TLS clearly poses an improvement in high resolution (both temporal and spatial) and a large range monitoring of a slow-moving landslide. Hereby, a major challenge is to differentiate surface changes related landslide movement to those referred to vegetation growth or loss. However, integration with the existing long-term, continuous monitoring system allows for a better characterization of the landslide kinematics in order to assess landslide hazard.

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P2.28

MEASURING SLOW-MOVING LANDSLIDE MODIFICATIONS IN BI-TEMPORAL DIGITAL SURFACE MODELS OBTAINED FROM HISTORICAL AERIAL PHOTOGRAPHS

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Purpose: The increasing availability of historical aerial images and of photogrammetric techniques offer an unprecedented opportunity for landslide scientists to corroborate heuristic interpretation by photogrammetric data. In this work, we compare two photogrammetric processing pipelines: a standard manual procedure and an automatic procedure developed for multi-epoch historical images (i.e. images acquired in different years) to obtain Digital Surface Models (DSMs). We tested the procedures to measure modifications of a slow moving slide-earthflow in South Italy between aerial photographs taken in 1954 and 2003. We also compared the results of the DSMs differences (DoDs) to an independent landslide map prepared by expert image interpreters.

Methods: The manual procedure, includes the following steps:

1. Intra-epoch processing: For images from the same epoch, we (i) apply an affine transformation of the original images to the geometry of the fiducial marks, (ii) apply feature matching based on SIFT, (iii) compute relative orientations based on the sequential SfM;
2. Inter-epoch processing: We (i) perform a manual identification of a denser network of common feature correspondences then acting as virtual GCPs in the next step; (ii) compute a rough co-registration of all epochs using Ground Control Points and a 7-parameter transformation;
3. Combined processing: Based on all GCPs we perform a joint bundle adjustment to refine all the image orientations and camera calibrations;
4. DSM computation: We computed the DSMs, for each epoch.

The automatic procedure can be summarized as follows:

1. Intra-epoch processing: For images from the same epoch, we (i) apply an affine transformation of the original images to the geometry of the fiducial marks, (ii) apply feature matching based on SIFT, (iii) compute relative orientations based on the sequential SfM and (iv) perform semi-global dense matching to get DSMs in their arbitrary coordinate frames;
2. Inter-epoch processing: We (i) roughly co-register the DSMs and image orientations from different epochs and (ii) perform precise matching under the guidance of the roughly co-registered results to reduce the matching ambiguity;
3. Combined processing: Based on the intra-epoch and inter-epoch feature correspondences, we perform a joint bundle adjustment to refine all the image orientations and camera calibrations;
4. Geo-referencing and DSM computation: Using a minimum of 3 Ground Control Points (GCPs) and a 7-parameter transformation we transformed the result from an arbitrary to an absolute frame. Finally, we computed the DSMs, for each epoch.

Results: The automatic procedure is more credible than the DoD computed by the manual approach, which produced a DoD characterised by a dome effect and by similar artefacts as the automatic procedure. Our results provided expert geomorphologists with new data to support and locally revisit the delineation of the event landslide that occurred in 2003. The new delineation of the event landslide includes an area 57% larger than the original map.

Conclusions: Despite several research questions remain open, our experiment proved that photogrammetry applied to historical aerial photographs is a precious source of data that may help produce more accurate landslide inventory maps and leveraging other relevant analyses within the landslide science community.

P2.29
AMBIENT-NOISE SHEAR-WAVE TOMOGRAPHY FOR LANDSLIDE STRUCTURAL MODELS RETRIEVAL FROM DENSE SEISMOLOGICAL ARRAYS

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Purpose: The versatility, cost-efficiency and easy deployment of seismic sensor nodes facilitate geophysical monitoring in environments that were previously inaccessible for instrumentation, and among them landslides and unstable slopes, most of the time located in remote mountains. Using nodes allows for the setup of dense arrays with sensor inter-trace distances that become compatible with the geometries and dimensions of the geological structures to image. This becomes particularly true for landslides which have complex 3D architectures (hummocky bedrocks, layering, multi-dimensional fractures, diverse geotechnical material, deep and perched aquifers and water circulations) and are shallow processes with respect to the classical investigation depths and sensitivity of most geophysical survey techniques.

Methods: Here we develop a specific processing workflow to allow the computation of 3D shear-velocity models with Ambient-Noise-based tomography applied to dense arrays of seismic stations. The workflow is applied to a dataset acquired at the Viella shallow landslide (France) developed in altered schists and moraine deposits. We deployed 70 IGU-16HR-3C-5Hz SmartSolo sensors (EOST/PISE service) with inter station distances of 70 m for a period of 25 days. The processing consists in several steps, all of them being tuned to the specific case of shallow depths of investigation. In areas where only few strong (ML>4) earthquakes are triggered, with a low azimuthal distribution, surface-waves velocity fields are complex to estimate with earthquakes. Ambient noise cross-correlation tomography has the advantage of using the ambient noise to model the surface waves velocities by retrieving the interstation Green's functions. The main hypothesis for retrieving the Green's functions is a homogeneous noise-source distribution, which is never achieved in a natural environment. Therefore, data filtering and daily stacking are crucial to reduce the effect of non-uniform noise distributions and lead to consistent velocity models. Due to the noisy environment of Viella (torrential flows, farming activity, anthropogenic noise), several procedures were implemented to optimize the processing (reduction of the coherent noises in the processed data, use of a pseudo-topography to estimate as accurately as possible the inter-station distances and travel times). We then computed the dispersion curve diagrams for the surface waves on which we applied a strict selection to only keep the consistent part of the surface waves dispersion curves. The selection parameters were optimized for the Rayleigh and Love waves. Then, we inverted the inter-station travel times to compute group velocities maps at several frequencies. Finally, we proceed to a Markov-Chain-Monte-Carlo inversion of each of the dispersion curves extracted from the group velocity maps. We finally obtained a 3D shear velocity model, which is further combined with geological and borehole information in order to document the 3D structure.

Results: The objectives are to present the processing workflow developed specifically for shallow imaging and the retrieval of 3D heterogeneities; effects of the processing parameters will be discussed on the Viella dataset.

Conclusions: The approach developed for Viella is generic and has been further applied to other geological processes (permafrost at the Chauvet rock glacier, Marie-sur-Tinée mudslide), and the models will be discussed.

P2.30

SPARSE GRADIENT ARRAY: A NEW APPROACH TO SELF-POTENTIAL LANDSLIDE MONITORING

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Tizzano Val Parma, a mountain municipality located on the Apennine chain in the province of Parma, is prone to landslides due to geological and geomorphological factors. In recent years, the hydrogeological instability induced by these landslides has caused significant environmental damages, making it essential to monitor potential instability in the local earth massifs. The Self-Potential (SP) monitoring method is an effective geophysical method for identifying anomalous water flows within landslides. If the concentration or speed of water flows or infiltrations reaches a critical level, it can trigger erosion or liquefaction processes. This can lead to subsidence, the movement of materials from the massif, and eventually, a partial or complete collapse of the landslide. By understanding the different sources of the SP method, it is possible to improve the accuracy of landslide monitoring and reduce the risk of potential hazards. Revil and Jardani (2013) identified different sources of the SP method, such as thermo potential, electrochemical potential, streaming potential or electrokinetic potential, and geobattery potential. In most cases of landslide application, it can be assumed that the SP anomalies have the electrokinetic flow potentials generated by water movement as the main source (Gallas, 2020; Heinze et al., 2019). This study proposes a new approach called Sparse Gradient Array, which is similar to traditional Gradient and Fixed-Base techniques, but with a significant difference: there are no reference measured points for successive measurements. The originality of our approach consists in using a new-concept Resistivity Distributed System, such as the Fullwaver system (MPT-IRIS — www. iris-instrument.com), to conduct sparse measurements. This passive system is capable of logging both artificial and self-potentials at a frequency of 100 Hz between multiple pairs of electrodes. A three-day monitoring survey was carried out for this study, on an active landslide in Tizzano Val Parma, acquiring the data for eight hours a day using the Sparse Gradient Array technique. The obtained responses were stable and repeatable, indicating a good coherence of the recorded signals. The data analysis allowed us to infer the existence of an anomalous flow along a preferential flow path and to locate the potential electrokinetic sources using the analytical amplitude signal through the Fast Fourier Transform. Furthermore, the transient SP logging analysis revealed probable water movements occurring below the electrode pairs. The use of the Fullwaver systems in the Sparse Gradient Array approach is an effective method for SP monitoring in landslide-prone regions. It allows for accurate monitoring of anomalous water flows and can provide early detection of potential landslide hazards. This new approach can improve the accuracy of landslide monitoring and reduce the risk of potential hazards in regions prone to landslides like that of Tizzano Val Parma.

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P2.31
A PREDICTION METHOD FOR INITIATION LOCATIONS OF LANDSLIDES AND SLOPE FAILURES BY THE EARTHQUAKES AND INTENSE RAINFALLS

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Purpose: To mitigate landslides and slope failures, it is necessary to predict the initiation location of the landform changes and the extent of the damages. LiDAR-DEM technology has advanced to a stage where it is possible to obtain detailed topographic information on real terrain surfaces. To clarify the mechanism of landslides and slope failures, the topographical characteristics of the triggering points of landslides and slope failures are to be identified by comparing the topographies before and after events, and a process-based hazard mapping method should be developed to estimate the mechanism of sediment transport and mass flow to take measures to mitigate damage. A new method to represent the detailed topographic features, a landslide hazard prediction map was developed using 1m (50cm)-LiDAR DEM.

Methods: To predict the location of landslides triggered by heavy rains and earthquakes, a landslide hazard prediction map was developed for landslides, slope failures, and debris flows based to observe the phenomena by the comparison of before and after events. This landslide hazard prediction map can visually represent landforms in a way that is easy to understand the topographic features using a 1m (50cm)-LiDAR DEM. Applying this method to several disaster cases was carried out, such as the debris flow disasters in Hiroshima in 2014, landslide disasters in North Kyushu in 2018, and the 2016 Kumamoto Earthquake in JAPAN, respectively. The landslide hazard prediction map is generated by the calculation of the amount of erosion and the gradient of the amount of erosion. To clarify the topographic changes before and after the events, firstly the comparison of the landslide hazard prediction maps and next the subtractions of the gradient of the amount of erosion were carried out.

Results: There are common topographical features at the initiation points of landslides and slope failures. Using this map, it is possible to identify where sediment transport initiates, there are common topographic characteristics. That is the lack of sustaining structure in the downslope, that is the edge of erosion fronts where the erosion processes are going upslope in the valley in case of intense rainfalls. Also, similar points and lines that are likely to collapse by earthquakes are located at the points and lines where there are no sustaining structures in the downslopes. From these points and lines, the collapse and the raptures are proceeding upslope in the landslides and slope failures. These locations are coincident with the lowest points in the longitudinal and transverse profiles with the lack of the cell in Okimura's model (1994).

Conclusions: The landslide prediction map using 1m-LiDAR DEM can detect the changes in topographic features and can be used to clarify the initiation processes and mechanism of initiation of the landslides and slope failures. The common topographic features of the initiation location of the collapse are located where there is a lack of sustaining structures under the slope. In the presentation, the areas of landslides and slope failures are to be represented using the mass flow simulation model iRIC and three-dimensional displacements caused by the 2016 Kumamoto Eq. can be detected by Particle Image Velocimetry using these landslide prediction maps.

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P2.32

MULTIPARAMETER GEOPHYSICAL SURVEYS FOR THE SITE CHARACTERIZATION OF LANDSLIDES ALONG THE HOCKAI FAULT ZONE, EAST BELGIUM

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Purpose: The seismically active Hockai Fault Zone in East Belgium hosts in its northern part more than 20 landslides (Quaternary palaeo-slopes and recent instabilities). The slopes are affected by subsidence, rotational movements, and flows, initially likely to have been triggered by earthquakes and recently reactivated by anthropogenic loading and precipitation associated with pore water pressure changes and internal erosion. The Manaihant landslide, located south of Battice (North-East of Liège), is a clear example of a recently reactivated instability phenomenon in this area. It is about 400 m wide and 250 m long. A large part of the landslide area is used as pastureland, but on the slope, there are several houses and a factory that have been affected by the movement, causing serious damages. The landslide movements were initially reactivated by the break of a waterpipe crossing the middle part of the slope and then continued after heavy rainfall events, resulting in average yearly displacements of about 15-20 cm.

Methods: In this work, geophysical techniques such as single-station ambient seismic noise (analysed by horizontal/vertical spectral ratio, HVSR or H/V), seismic refraction tomography (SRT), multichannel surface wave analysis (MASW) and electrical resistivity tomography (ERT) were used to characterise the landslide area and, through a geomodelling approach, subsequently create a clear 3D geological model of the subsurface. By taking 65 H/V measurements in different geomorphologically significant areas, it was possible to characterise the thicknesses of the strata. The seismic velocity distributions (P- and S-wave velocities), together with the electrical resistivity, made it possible to further characterise the internal structure of the slope.

Results: H/V measurements identified frequencies of 3Hz, 4Hz (typically in the upper parts marked by the presence of thicker and softer deposits) and 6Hz (in the lower part where the earth flow thins out). Seismic tomography showed the presence of two main layers with P-wave velocities of 800 m/s and 1500 m/s, respectively. Electrical tomography also confirmed the presence of the two main layers with resistivities of 10-20 Ωm in the upper part and 400-500 Ωm in the deeper layer. The geophysical investigations inferred a surface layer of looser material overlying an intact conglomerate. The contact between the two media would probably be attributable to the sliding surface. The depth of the landslide tends to decrease towards the valley, with layers thicknesses between 7-9 m and 17-20 m.

Conclusions: The results of geophysical surveys can be integrated into a 3D geomodel, which allows the data collected from direct and indirect surveys and geomorphological observations to be visualized and jointly analysed. The 3D geomodel of the landslide built from the integrated use of different geophysical techniques, with stratigraphic and geomorphological observations, digital terrain model and field survey data will allow, in future studies, to contribute to the reconstruction of a reliable slope stability model.

P2.33
MOBILE APPLICATIONS OF L-BAND SYNTHETIC APERTURE RADAR IN ALPINE ENVIRONMENTS

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Applications of satellite SAR imagery in mountain environments range from the identification and mapping of flooding, snow cover monitoring and avalanches documentation, landslide detection and monitoring of slope deformation, response of forests to droughts, estimation of biomass parameters, effects of insects outbreaks on plants, and evaluating the impact of forest fires. Currently, numerous satellite missions provide an increasing amount of SAR data to monitor the Earth's surface, and a variety of new programs are planned for the near future. Despite these great advancements, several problems remain for the full exploitation of spaceborne SAR imagery in mountain regions. In particular, the revisit time of satellites is of several days or weeks, limiting permanent monitoring applications. Moreover, ground resolution and geometry of acquisition from satellites is not always optimal to suitably observe local phenomena in areas affected by steep slopes. In addition, rapid changes of the scene often occurring in alpine scenarios due to snow cover, vegetation cycles, erosion, rockfalls, may cause partial or complete loss of information due the decorrelation of the SAR signal.

The project MiSURA, (Mobile Applications of L-Band Synthetic apertUre Radar in Alpine environments), aims at evaluating the systematic use of the newly developed GAMMA L-Band SAR to detect, map, and monitor different environmental variables in alpine settings. We set up a unique pilot project to: (i) understand and evaluate the survey and monitoring capabilities of mobile L-Band systems in different operational conditions; (ii) identify pros and cons compared to satellite imagery and other remote sensing methods; (iii) analyze accuracy and reliability of the measurements provided. We will mainly investigate slope displacements in complex alpine settings and in permafrost areas, but also analyze the potential of L-band measurements to detect changes in vegetated areas and in channels prone to debris flow activity. To this end, two campaigns each of one week with daily car-borne L-band measurements will be performed in the Canton Grisons, Switzerland, at pre-selected locations. The validation and integration of the L-band car-borne measurements into operational frameworks, as well as feedback from stakeholders and authorities is also an important aspect of the project. Moreover, the results of systematic use of terrestrial L-Band products will provide important hints for the use of future datasets acquired by the new satellite missions.

P2.34
REGIONAL CHARACTERIZATION OF PERIGLACIAL FEATURES IN ALPINE ENVIRONMENT BASED ON DINSAR PHASE AND PERMAFROST EXTENT

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Periglacial landforms like rock glaciers and protalus ramparts are key indicators of the state of permafrost in periglacial environments and represent important climatic proxies. In particular, rock glaciers are characterized by a composite and heterogeneous internal structure, resulting in complex deformation mechanisms and time dependent behavior with seasonal and episodic accelerations which can lead to destabilization and collapses of frontal and side sectors. A robust quantification of the style of activity of periglacial landforms is thus fundamental to understand their dynamics in a geohazard perspective. In this context, while only few of them can be characterized by site investigations and ground-based monitoring, DInSAR proved to be a powerful tool to characterize their rates of deformation, but quantitative approaches able to automatically classify entire inventory datasets on the regional scale are still lacking.

Here, we developed a novel procedure in ArcGIS and Matlab TM combining DInSAR products, morphometric data and available permafrost extent information (APIM) to exploit the potential of spaceborne DInSAR analyses and characterize the state of activity of 514 rock glaciers over an area of approximately 1000 km2 in the north-eastern sector of Valtellina (Italian Central Alps). To obtain a spatially distributed characterization of rock glacier activity patterns, we processed Sentinel-1 A/B images (2017-2020) with increasing temporal baselines (Bt from 12 to 120 days) and generated 124 interferograms in ascending and descending geometry to account for all the different topographic orientations. We then implemented an analysis of the interferometric phase to achieve a quantification of each rock glacier activity based on four analytical steps: a) definition of stable reference areas for each inventory of periglacial feature; b) correction of unwrapped interferometric phase values within each feature with reference to their stable reference area; c) stacking of the corrected wrapped interferograms generated with same temporal baseline; d) analysis of the median phase value distribution inside each rock glacier and stable area, and quantification of an ordinal Activity Index (AI).

Classification results based on DInSAR data at different temporal baselines allowed recognizing styles of activity characterized by spatial and temporal heterogeneities with different ranges of displacement rates.

The final classification grouped all the mapped landforms in four activity classes: active, inactive, active debris and relict. Multivariate statistical analysis and density plots on morphological parameters and morphometric categories support our results providing an insight on the spatial distribution of the intact and relict forms giving clues on the controlling variables interplaying in the definition of their state of activity.

Our methodology can be applied to other alpine areas and datasets for a wide-area evaluation of rock glacier activity for climatic studies and possible site specific investigations.

P2.35

ANALYSIS OF THE UNSTABLE SLOPE ABOVE PORTAGE GLACIER (ALASKA) THROUGH CONVENTIONAL AND REMOTE SENSING APPROACHES

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Catastrophic rock-slope failures associated with glacier retreat and thinning are often studied only after the failure has occurred. However, studying movement of at-risk slopes is important for better understanding the precursors to slope failure, especially the interaction between glacier retreat and rock-slope stability. The site of interest, located at Portage Glacier on the Kenai Peninsula in Alaska, provides an ideal opportunity to study how glacier retreat affects rock-slope dynamics. This site exhibits many hazard factors, including rapid glacier retreat and thinning, high and steep slopes, signs of active fracturing along the current instability scarp, and deep water with potential for tsunamis caused by a possible rock-slope failure. The slope shows signs of a progressive failure, presumably related to the glacier retreat and thinning. The instability has so far developed in two phases of slope destabilization. During our field campaigns, we collected structural measurements, completed repeated long-range terrestrial laser scans, and carried out photogrammetric surveys. The combination of conventional structural mapping and remote sensing methods allows us to better understand the structural framework and the degree of damage within the slope. The goal of this study is a detailed analysis of the processes that influence how the slope responds in time and space to changing external influences and internal conditions.

P2.36

GLOBAL INVENTORY OF LANDSLIDES MOBILISING ICE-CEMENTED GROUND AND THEIR ASSOCIATED LANDFORMS

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Purpose: Landslides in alpine environments can occur in zones of discontinuous or continuous permafrost where ground ice is prevalent. We have been investigating landslides where blocks sediment cemented with ground ice have been mobilised and deposited downslope. These blocks degrade to form mounds of loose debris, which are often conical in shape and are called permafrost molards. Therefore, the presence of conical mounds in landslide deposits can be good markers of the presence of permafrost in the landslide detachment zone and this link motivates this study.

Methods: We compiled an inventory of molard-hosting landslides using: the published literature, personal communication from researchers and ad hoc detection using satellite images. We used the published literature to ascertain the local geology and the state of permafrost in the region of each landslide. We used stereo satellite images to produce digital terrain models for many of these landslides using digital photogrammetry. We delimited the landslide, estimated its length and fall height and mapped the distribution of conical mounds.

Results: We find landslides associated with conical mounds in every major region of mountain permafrost, including the Rocky Mountains, the Andes, the Himalaya, Kamchatka, and the fjordlands in Greenland, Norway and Iceland. The landslides are predominantly mobilised in surficial materials including talus aprons, glacial deposits and rock glaciers. They occur in various permafrost conditions, from continuous to isolated. The landslides have a variety of types, including debris flow, debris avalanche and rock avalanche. There is no simple relationship between the reach angle (fall height divided by length) and the distribution of conical mounds, nor between the permafrost state and either of these variables.

Conclusions: Our work establishes the first global inventory of landslides hosting conical mounds which we interpret to be permafrost molards. In the context of changing climate, landslides in degrading permafrost, could become more prevalent, so it is timely to better understand these mass movements and their associated landforms. Their documentation is the first step. Our future work will investigate how the molard shape and distribution in these landslides could provide additional information on the rheology of the landslide and the type/quantity of ground ice in the detachment zone.

P2.37
LANDSLIDE DETECTION AFTER EXTREME CLIMATE EVENTS IN THE PROVINCE OF BELLUNO (VENETO REGION, NE ITALY)

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Purpose: Following extreme climate events, timely and comprehensive landslide detection is necessary to identify the most affected areas and to support civil protection and rescue operations. Landslide detection remains challenging in location where the land cover has changed drastically, as this makes landslide identification difficult areas where forests have been destroyed. In 2018, the province of Belluno (Veneto Region, NE Italy) was hit by a significant and intense meteorological event, namely, storm Vaia. Heavy precipitation of up to 600 mm in 72 hours, combined with strong winds of up to 200 km/h, caused widespread landslides and forest damages of 8,680 hectares. In this study, our objective is to identify a synergic approach to landslide detection in this area where several windthrown have yet to be harvested.

Methods: To identify and describe landslides triggered during windstorm Vaia in the province of Belluno, SAR and optical parameters were measured inside landslide polygons established as part of the "Valuation and Application of Innovative Approaches in LANDslides Risk Mitigation" (VAIA-LAND) project. Similar criteria have also been applied to differentiate landslide areas from the windthrown area. In particular, medium- and high-resolution SAR data, such as the C-band Sentinel-1 and the X-band COSMO-SkyMed, have been used to refine landslide detection by calculating various statistical parameters derived from amplitude and coherence information; optical imagery acquired by Sentinel-2 and PlanetScope missions have been integrated to calculate pre- and post-event Normalized Difference Vegetation Index (NDVI) values.

Results: The results show how the various sensors operate in this challenging area, as well as how the definition of statistical parameters might help in the detection of landslides and forest areas destroyed by the Vaia event. In this case study, amplitude derived from high-resolution COSMO-SkyMed data reveals more distinct differences between pre- and post-event variations than coherence information and medium-resolution Sentinel-1 data. Moreover, the integration of these outcomes with optical sensors allows for improved landslide detection.

Conclusions: In conclusion, our technique highlights the benefits of integrating SAR and optical data for landslide detection, and it also contributes to recognising areas affected by forest damage following a severe event such as windstorm Vaia.

P2.38

EROSION DYNAMICS AND DEBRIS FLOW HAZARD IN A CHANGING CLIMATE: THE CASE OF THE DAR RIVER, AN ALPINE TORRENT IN SWITZERLAND

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Purpose: The Dar River, situated in the Diablerets Massif in the Swiss Prealps, comes down from the Sex Rouge Glacier through the cirque of Le Dar Dessus, the Dar cascade and then borders the massif with a southwest direction before joining the Grande Eau River which then crosses the village of Les Diablerets, a major tourist destination in the area. In spite of the many hazards historically present in the Grande Eau catchment - avalanches, landslides, and floods - the Dar is less well studied, and bedload and debris flow hazards have been only partially explored; even if in 2005, a flooding event affected the village of les Diablerets. Under current and expected future climatic conditions, river dynamics and in particular the occurrence of extreme events such as debris flows and bedload, pose a threat to the safety of tourists and villagers and to the built infrastructure, and consequently to the long term prosperity of the area. Glacier retreat for the Sex Rouge due to climate change is well documented and the glacier is expected to disappear completely by mid-century. This, along with the forecasted more intense precipitation events, as well as rapid snow melt due to hotter winters will invariably change the water input, erosion and sedimentation dynamics downstream, and most importantly, triggering conditions for debris-flows and high-bedload transport. Additionally, the river profile is complex, with tectonic and structural control in various segments resulting in several nick points, and a sharp left turn after the last cascade, before adopting a more meandering pattern downstream. Here we study the dynamics of this alpine catchment and assess potential short, and midterm changes expected due to climate change, as well as potential debris flow occurrence in order to better constrain the hazards associated with this catchment and the elements at risk in the area.

Methods: Historical aerial images, Lidar scans, and periodical monitoring were used to identify current erosion and accumulation zones. Wildlife cameras were used to study the river dynamics, and modelling outputs for runout zones using different software (Flow-R and RAMMS) were compared. Zones where debris flow hazard is present were identified and a qualitative assessment of future conditions, including changes in triggering conditions due to climate change were analyzed.

Results: Historical images from the last 50 years show clear changes in the trace of the streambed, with riverbank erosion and streambed enlargement in the lower part of the catchment, and gradual unearthing of the bedrock in the upper part of the catchment. Sediment pulses are observable and contributions to debris-flows by landslides affecting the riverbank are expected to increase.

Conclusions: Seasonality of extreme events and triggering conditions are expected to shift, but the exact contributions of snowmelt versus precipitation for a high-density event are still not yet well constrained. Future work includes a quantification of the changes in return periods for extreme precipitation events in this catchment and the resulting potential events (flooding with bedload and debris flow) in these circumstances.

P2.39

DYNAMICS AND CONNECTIVITY OF SLOW-MOVING LANDSLIDES IN CHANGING TROPICAL LANDSCAPES

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Human activities transform Earth's ecosystems and landscapes at unprecedented rates and scales. Land use changes are particularly drastic in economically developing countries of the tropics, where major demographic and economic shifts are driving unparalleled rates of agricultural expansion, deforestation and urbanisation. These changes to the environment are increasing the incidence of geo-hydrological hazards such as landslides. Dramatic increase in the occurrence of shallow, high-velocity landslides has been comprehensively demonstrated on recently deforested and/or urbanised steep slopes. Yet, our understanding of how such constraints – typical for the tropics – interact and affect larger (often > 0.2 km^2), slow-moving (mm year−1 to 100 m year−1), deep-seated (> 5 m) landslides (SML) remains very limited. Often manifesting as long-term, persistent slope failures, these SML can nevertheless permanently affect the livelihood of local communities in mountain regions. Their connectivity to river networks also places them as a dominant geomorphic process in mountain landscapes: they shape the morphology of hillslopes and can exert very strong controls on river sediment budgets, regional erosion rates, channel network evolution and flooding patterns. Nevertheless, estimations of landslide mobilisation rates over sufficient spatiotemporal scales are very scarce, especially in tropical environments. As a result, the potential interactions between rivers and landslide dynamics remain poorly constrained while being key for our understanding of landscape evolution, sediment budgets and geo-hydrological hazards.

Untangling the intricate influences of climate, lithology, tectonics and man-made environmental changes on the activity of SML will require a large and robust dataset across diverse landscape conditions. Here, we aim to present and discuss our strategy is to quantify SML spatio-temporal patterns over the western branch of the East African Rift System (wEARS), a > 1000 km north-south region exemplary of many tropical mountain areas, i.e., affected by large-scale land use changes and disproportionately high landslide impacts – as well as largely overlooked in landslide research. Synergies between different space-borne remote sensing tools (combined use of optical and radar imagery, historical aerial photographs, etc.), which proved effective in our recent work in the region, will be exploited to gather a large dataset on the activity of SML across diverse time scales, landscapes and climatic conditions in the wEARS. Overall, this work aims at moving forward our understanding of a key geomorphic process in severely under-researched types of environments subject to rapid changes. This is not only essential for a better hazard assessment, but also for comprehending how (human-induced and/or natural) environmental changes affect these landscapes and the sediment dynamics.

P2.40

THE CAPABILITY OF COUNTY-LEVEL GROUND MOTION INTERFEROMETRIC SERVICES OF DETECTING AND MONITORING LANDSLIDES IN ALPINE REGIONS: THE CASE OF SWITZERLAND

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Since the launch of the first SAR missions, in the 90s, the use of SAR interferometry and multi-temporal SAR interferometric technique proved their effectiveness on measuring surface deformations in different scenarios, with a wide use in case of landslide monitoring. The effectiveness of these remote sensing techniques led to the development of many applications in the last 30 years. Recently, thanks to the availability of the world-wide coverage and freely accessible Sentinel-1 SAR data, the application of interferometric techniques is address to wide areas with frequent updates, trying to automatize the data processing as possible and extending the solution to wide areas, to provide systematic solutions at regional level, county level, up to cover all Europe. In this context, Copernicus supported the European Ground Motions Service (EGMS) while, in Switzerland, a similar service has been implemented thanks to a procurement of the Swiss Federal Office of Topography. This study can provide information about geohazards as well as human induced deformations, slow moving landslides, subsidence, infrastructure stability,… The implementation of large scale studies implies the identification of the processing parameter best setting as well as a degradation of the data resolution, at least in case of distributed scatterers, to make the data processing computationally affordable. Therefore, this approach is not optimizing the analysis of a single slope or a specific deformation event.

Hence, the purpose of the present work is to analyze the capability of country level ground motion services on detecting landslides in alpine regions, providing useful information for mapping and monitoring purpose. In addition a deep analysis is carried out to understand the reason of the partial information loss, to identify and discuss different limitation scenario, due to the degraded resolution, snow cover conditions in different contexts, parameters settings, slope dynamics, morphology, etc.

This work allowed assessing how the existing land motion projects covering wide areas can help, partially substitute, guide or integrate local scale studies on landslide deformations.

P2.41
MULTI-TEMPORAL SAR INTERFEROMETRY TECHNIQUE FOR STUDYING SLOPE INSTABILITY PHENOMENA AND THEIR EVOLUTION

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Purpose: Multi-temporal SAR interferometry (MTInSAR), by providing both mean displacement maps and displacement time series over coherent objects on the Earth's surface, allows analyzing wide areas, identifying ground displacements, and studying the phenomenon evolution at a long-time scale. In particular, early warning signals derived from MTInSAR displacement products may be very useful for decision-making processes in the risk assessment phase. This study exploits the potential of COSMO-SkyMed (CSK) and Sentinel 1 (S1) satellite missions to investigate ground and structure displacements related to the slope instabilities. Furthermore, it investigates methods for the automatic identification of nonlinear displacement time series that reliably support the analysis of the huge quantity of coherent targets nowadays available from MTInSAR processing chains.

Methods: This work presents the results obtained by analyzing displacement time series from both CSK and S1 for investigating the ground stability of hilly villages located in the Southern Italian Apennines. Both ascending and descending orbits were processed by using the SPINUA MTInSAR algorithm. Mean velocity maps and displacement time series were analyzed, looking, in particular, for non-linear trends that are possibly related to relevant ground instabilities. This analysis was also supported by automated procedures recently developed, one based on the fuzzy entropy (FE) indicator, the other performing nonlinear trend analysis (NLTA) based on the Fisher statistics. The FE index was able to recognize coherent targets affected by phase unwrapping errors, which should be corrected to provide reliable displacement time series to be further analyzed. The NLTA was used for classifying targets according to the optimal degree of a polynomial function describing the displacement trend. This allowed the focus on a smaller set of coherent targets showing nonlinear displacement trends related to the several ground and structure instabilities.

Results: The joint exploitation of MTInSAR datasets acquired at different wavelengths, resolutions, and revisit times provided valuable insights, with CSK more effective over man-made structures, and S1 over outcrops. Both automated procedures were very effective in supporting the analysis of ground displacements provided by MTInSAR, since they helped focusing on a smaller set of coherent targets identifying unstable areas or structures on the ground. In particular, the work presents examples concerning [1]: (i) slope pre-failure monitoring; (ii) slope post-failure monitoring; (iii) displacement evolution monitoring of areas and structures affected by instability related to different causes.

Conclusions: These results clearly confirm the valuable use of MTInSAR products as a tool that is additional to the established techniques for studying the dynamics of slope instability phenomena and their evolution. The analysis of MTInSAR-based displacement time series, possibly performed through ad hoc automated procedures, can provide useful information for long-term monitoring, management, and risk assessment at the regional level, when combined with planning tools, and support decision-makers at a local level in risk management.

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P2.42
EVALUATING UNSUPERVISED ANALYSIS OF LARGE SATELLITE INSAR DATASET IN THE ITALIAN ALPINE AND APENNINE MOUNTAIN REGIONS

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Purpose: The aim of this research is to manage, analyse and interpret large multitemporal satellite interferometric (InSAR) dataset to evaluate spatial and temporal patterns of ground motion. Here we design, implement, test and validate an automated ground motion analysis system in the Alps and Apennines (Italy) in order to assess its applicability in various geological, geomorphological, and climatic contexts. The focus will be the definition of the typology and kinematic of landslides.

Methods: For systematic large-scale mapping (i.e., from regional to national scales), the large volume of InSAR information enclosed within millions of point-wise measurement points (MPs) dictates the need for efficient data mining approaches to reveal the underlying displacement patterns. The method proposed here is the unsupervised and automated approach based on Principal Component Analysis (PCA) and K-means clustering to detect patterns of natural or human-induced ground deformation from satellite interferometric Time Series (TS-InSAR). PCA allows us to extract the most meaningful basis of a given data set. These are then clustered by the K-Means algorithms allowing the definition of spatially and temporally coherent displacement data. The adopted TS-InSAR data mining approach is entirely performed in automated fashion by running an original code assembled in Python. The rationale consists of a stepwise procedure: i) spatial and temporal resampling of the InSAR dataset to interpolate and calculate vertical and eastward displacement component; ii) PCA-based dimensionality reduction and features retrieval; 3) unsupervised K-Means learning for automated clustering.

Results: The application of the assembled code in Alpine and Apennine regions showed the potential of the approach. TS-InSAR targets from different geometries of satellite acquisitions were reprocessed into several thousands of square cell features containing the temporal displacement trends of the eastward and vertical components of motion. The analysed features demonstrate to be spatially clustered in accordance with the varying morphometry of the terrain and with the described surface motion phenomenon. The presented method shows its full potential for the detection and characterization of different patterns of motion when looking at local unstable areas affected by different types of landslides. Using this procedure, it is possible to detect both linear and seasonal displacement behaviours using the large volumes of Sentinel-1 data.

Conclusions: The large amount of multitemporal dataset in the context of SAR interferometry analysis urges the implementation of an automated ground motion analysis system in the framework of geohazard risk management. The deployed code provides processing performances resilient to the ever-increasing volumes of SAR data and an automatically balanced cost-benefit strategy to produce accurate outputs for stakeholders in need of handy tools for territorial planning operations and civil protection purposes.

P2.43

INSAR-BASED MONTHLY UPDATED GROUND MOTION TIME SERIES FOR DETECTING VELOCITY CHANGES ON ACTIVE LANDSLIDES

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Over the last 10 years, thanks to the development of platform-based services (e. g. the European Copernicus Service) a number of studies based on InSAR data for monitoring land displacement can be found. However, only few of them include the development of automatic real-time processing that could be integrated in Early Warning System (EWS). In particular, few studies propose to include frequently updated interferometric Time Series for landslide risk assessment at a regional scale, with the aims of automatically detecting significant velocity changes in the last weeks/months of the Time Series. The definition of warning thresholds adapted to the expected motion is one of the main issues for such an application and will be investigated.

It is proposed in this study to develop an automatic production of ground motion Time Series, using monthly updated INSAR data detecting significant velocity changes. The approach will be applied to landslides monitored by other means (ground based) in order to have validation data.

More specifically, it is planned to produce ground motion Time Series using Spaceborne SAR Interferometry (INSAR) on the landslides during the duration of the project, with monthly updates. The objective is to assess the interest of this technique as ancillary information to be combined with other information (ground monitoring, susceptibility maps…) in the perspective of warning analysis. For producing ground motion information on the area, we will use approaches based on PSI (Persistent Scatterers Interferometry) and/or SBAS (Small Baseline Interferometry) for processing SAR (Synthetic Aperture Radar) data acquired by space-borne platforms such as Sentinel 1, but not only.

The specificities of landslides with respect to space-borne INSAR techniques are related to i) land-cover - generally partially vegetated – which as a consequence results in a reduced density of PS points ; ii) a fast kinematic, which may impact INSAR performances (i.e. mean velocities larger than several cm/yr) with a significant non-linear behavior (notably seasonal accelerations are expected). For these reasons, we will focus on short time-span interferograms during the processing in order to reduce loss of coherence.

For that, it is planned to process data from the Sentinel-1 A/B sensors archive and to recover new data each 6 or 12 days on the area of interest. We propose to process 1 or 2 years before the T0 of the project and update regularly by adding 1 month of new archive in order to detect possible evolutions in the displacement rates. For the different test sites, thresholds values on the updated motion rates will be investigated in the perspective of automation of the process for EW approach. The processing will be mainly based on the SNAPPING service of the geohazards tep (https://geohazards-tep.eu/). Gamma (https://www.gamma-rs.ch) tools will be used as a potential alternative.

P2.44

ANALYSIS OF DIFFERENT OPERATIONAL RAINFALL DATASETS AND THEIR IMPACT ON SLOPE STABILITY

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Purpose: The factors influencing hillslope stability are multiple (e.g. climate, geology, geomorphology, hydrology) and among these, rainfall is widely recognised in the scientific literature as the main triggering one (Wieczorek, 1996; Guzzetti et al., 2007; Segoni et al., 2014). Determining the critical amount of rainfall needed to trigger slope failures is a challenge in Landslides Early Warning Systems, especially in climates characterized by extreme precipitation. The aim of this study is to assess the reliability of different operational rainfall datasets in landslides forecasting.

Methods: The analysis is carried out through the application of the TRIGRS code (Baum 2008) using four different precipitation input, respectively obtained by: a) the rain gauge network; b) the satellite observations by GPM (Global Precipitation Measurement) Mission; c) the ground radar observations; and d) the combination of radar and rain gauge observations through the Modified Conditional Merging technique (MCM, Bruno et al., 2021). The study area is a well-known shallow landslide occurred in Umbria (Central Italy) in the past.

Results: The four rainfall datasets used show different characteristics in terms of both hourly intensity and accumulation. The performance are evaluated through contingency matrix and skill scores.

Conclusions: The use of rainfall measurement by ground radar can provide a better estimation of precipitation and therefore improve the skill in landslide forecasting, especially for localized events. In fact, atmospheric processes generating extreme precipitation often take place over small spatial (e.g. <1km) and temporal (e.g. sub-hourly) scales that are rarely observed and recorded by rain gauges and satellite-borne systems (Lengfeld et al., 2020). On the other hand, satellite rainfall products are revealing more and more their potential due to their wide coverage and increasing tempo-spatial resolutions.

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P2.45

SURFACE SOIL MOISTURE ESTIMATE BY INTEGRATION OF REMOTE SENSING AND LOW-COST FIELD SENSOR NETWORK

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Purpose: Surface Soil Moisture (SSM) is a fundamental information in the unsaturated soil mechanical analysis, and its variations induced by rainfall can be evaluated by low-cost ground-based monitoring networks integrated with remote sensing techniques. Starting from previous studies on field installation and calibration of low-cost soil moisture monitoring networks using WaterScout SM100 sensors, the present research aims to implement a new and innovative procedure based on the integration of microwave products and multispectral data with ground-based soil moisture sensors for SSM estimate.

Methods: Soil moisture monitoring networks were installed in Mendatica and Ceriana – Mainardo (Liguria, Italy) over rainfall triggered landslides. The networks have been calibrated on the soil-specific characteristics of the areas to increase data accuracy. Obtained soil moisture data represent the ground truth on which remote sensing procedure for SSM estimate can be calibrated/validated. Consequently, the reliability evaluation of ground-based soil moisture data is a crucial phase. Soil moisture monitoring network reliability has been assessed through the normalized cross-covariance analysis between soil moisture data, recorded by network nodes, and rainfall. Each measurement node is equipped with four sensors inserted at different depth (-10 cm, -35 cm, -55 cm, -85 cm) on a vertical line. SSM estimate through remote sensing is carried out by considering microwave and multispectral images. Microwaves can cross obstacles like clouds, haze and light rain. They have a daily revisit time, but their spatial resolution (1 km) is too low to analyse landslides. Multispectral images have a higher spatial resolution (10 m), but they have a revisit time of three days, and they cannot overpass clouds and other atmospheric obstacles. Consequently, a procedure to integrate both kinds of images is necessary, in order to have SSM information over wide areas at an optimal spatial and temporal resolution.

Results: One of the main results is related to soil moisture monitoring network reliability analysis. The elaborations led to encouraging results, since the response of soil moisture sensors to rainfall is consistent with the expected infiltration process. In Figure 1, an example of soil moisture data collected by one measurement node of Mendatica monitoring network is presented.

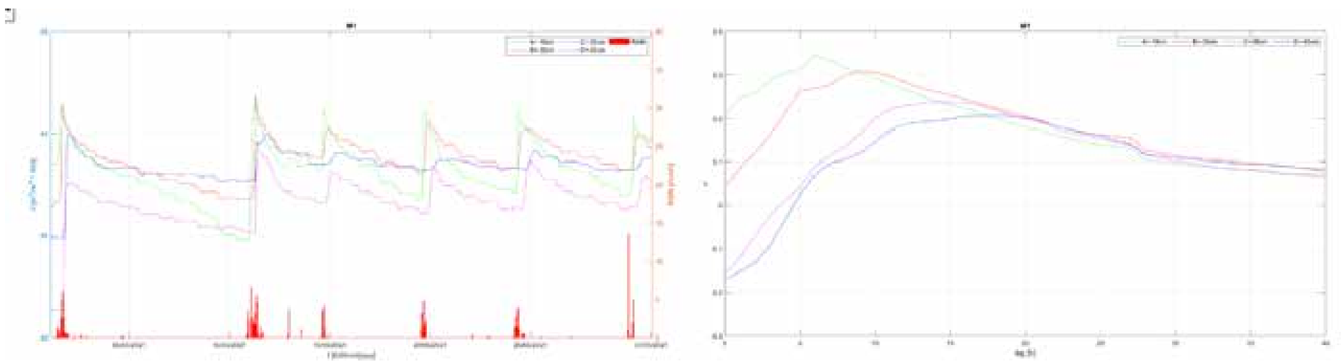

Fig. 1: (left) rainfall and soil moisture referred to M1 node in May 2021. (right) Soil moisture-Rainfall cross-covariance referred to node M1 in May 2021.

At the present time, the elaborations of multispectral and microwaves images for SSM estimate are still in progress. Currently, an analysis on Sentinel-2 multispectral images is being conducted with the purpose of correlate the available bands with the ground-based soil moisture data.

Conclusions: High resolution SSM information over large areas, obtained by the use of direct and remote sensing, can be used for monitoring and predicting rainfall triggered landslides. The low cost of soil moisture monitoring networks, together with the use of open access remote sensing products, underlines the global sustainability of this study.

P2.46

A NEAR-REAL-TIME AND DYNAMIC LANDSLIDE HAZARD FORECASTING FRAMEWORK FOR THE LOWER MEKONG REGION

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Purpose: The objective of this study is building a robust, cloud computing and machine learning based framework to provide landslide hazard forecasting over Lower Mekong region. This work was part of a collaboration efforts between the Asian Disaster Preparedness Center and NASA's SERVIR Program to increase the awareness of landslide hazards in the LMB through the Landslide Hazard Assessment System for Situational Awareness model (LHASA-Mekong).

Methods: In this research, a downscaled version of National Centers for Environmental Prediction (NCEP) provided Global Ensemble Forecast System (GEFS) precipitation generated by Climate Hazards Center InfraRed Precipitation with Stations (CHIRPS) was used. This dataset provides daily rainfall forecasts for up to 15 days at high spatial resolution (5km). The methodology first evaluates the spatiotemporal performance of CHIRPS-GEFS over the LMB for extreme rainfall events. Forecasted rainfall up to 3 days ahead is evaluated against the regionally corrected final version of the Integrated Multi-satellitE Retrievals for GPM (IMERG). Subsequently, forecast rainfall from CHIRPS-GEFS was combined with antecedent soil moisture and multiple topographic and lithological variables such as slope, relief, distance to roads, distance to faults, distance to rivers, topographic wetness index into the extreme gradient boosting (XGBoost) decision tree-based machine-learning framework. Landslides inventories spanning from 2015 to 2019 was used in the training of the model, while events from 2020 to 2021 was used for the validation of the model. The performance of the LHASA-Mekong forecast model is compared against the near-real-time version of the model for both retrospective and event-based scenarios. Finally, the model was implemented in Google Cloud Platform backed by Google Earth Engine for smooth and timely landslide hazard forecast without depending local computational resources.

Results: The generated hazard probability maps were compared for different lead times and nowcast model generated probability for six different landslide events. Among these events, the true positive rate over the training-phase inventories were more than 75% with exceptions. During the validation against three inventories from the validation period, the true positive rate was much higher with more than 80%. When the model was compared with the nowcast qualitatively, the resulting landslide hazard probability were matched quite well each other. These comparisons demonstrated that the model was able to generate forecasted landslide probability for up-to 2 days lead time with acceptable accuracy. There was a tradeoff between true positive rate and false positive rate need careful consider from users which partly depends on the threshold of the landslide hazard probability threshold.

Conclusions: Results demonstrate the advantages of the high-resolution CHIRPS-GEFS dataset for forecasting landslides in LMR. At the same time, the LHASA-Mekong forecast model shows a flexible architecture that can be used in cloud-based platforms such as Google Cloud Platform for landslide forecasting at multiple spatial scales. More accurate and locally relevant forecasted precipitation is anticipated to yield better hazard probability at the same lead-times. A rigorous comparison of different globally available rainfall forecast products and downscaled global products can help to inform the end users with more confident and reliable forecast of landslide hazards.

P2.47

ATTEMPTS TO DETERMINE GROUND SURFACE DISPLACEMENT USING INCLINOMETERS ON DEEP-SEATED LANDSLIDES RISK AREAS. THE CASE OF NAGANO PREFECTURE, JAPAN, IN THE JURASSIC ACCRETIONARY PRISM AREA

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It has become clear that deep-seated landslides occur when slopes are deformed by gravity in the characteristic geological structure (Chigira et al., 2013), and using these characteristics as keys, it may be possible to predict the occurrence site and the occurrence risk. We investigated the relationship between deformed slopes and geological structures in Tatsuno Town, Nagano Prefecture, Japan, where Jurassic accretionary prism is distributed. It was found that gravity-deformed slopes with deep-seated landslide risk areas were found to be concentrated near the fault zone with a maximum width of 300m, which develops in the mudstone-dominant layers near the boundary of the accretionary prism unit (Matsuzawa, Kimura; 2022).

Therefore, in this study, we measured the slope displacement using an inclinometer on two of the deep-seated landslides risk areas clarified by Matsuzawa and Kimura (2022) to determine the occurrence risk of deep-seated landslides. These two slopes have a clear gravity deformation topography, and a high potential for extensive damage in the event of a landslide. The inclinometer used is capable of real-time measurement with an accuracy of 0.01° and the inclination sensor was set up 1 m below the ground surface. Inclinometers were installed in December 2022 at six sites, three on Slope 1 and three on Slope 2.

Slow displacements with continuous accumulation in one direction were observed at two locations on slope 1. The maximum value of slow displacements was 0.007° between 12 December 2022 and 25 January 2023, suggesting that the slope was deformed by gravity. At one site, rapid movements were occasionally noted, such as up to 0.13° in one day, but these were not linked to movements at the other two sites and were assumed to be localized surface movements. Slope 2 showed slow displacements that continuously accumulated in one direction at all three sites. The maximum value of slow displacement was 0.026° between 12 December 2022 and 25 January 2023, which was greater than slope 1. However, as the direction of movement of the slope displacement was different at the three points, it was assumed that the entire slope was not sliding uniformly, but in several blocks.

Less than two months have passed since observations with inclinometer began, but we confirmed slow displacement, which is assumed to be due to gravity deformation, on both slopes. Continued observations of slope displacement by inclinometers and GPS surveys will be carried out in the future to determine the displacement characteristics and the risk of occurrence of deep-seated landslides risk areas.

P2.48
CELL SIZE EFFECT ON LANDSLIDE SUSCEPTIBILITY MAP OF TASIKMALAYA REGENCY, WEST JAVA PROVINCE, INDONESIA

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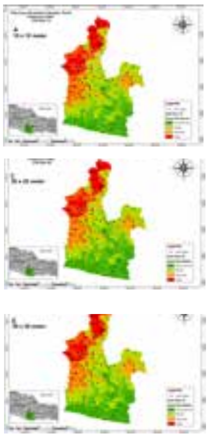
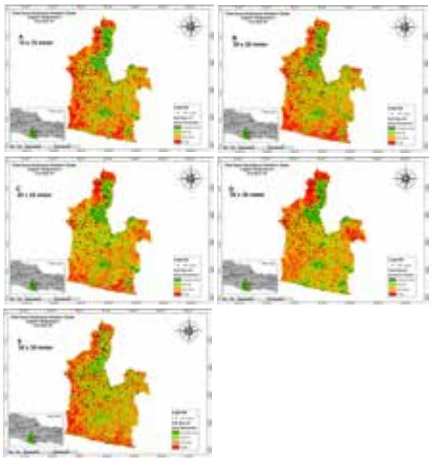
Purpose: Landslide is Indonesia's most frequent natural disaster, especially in the Tasikmalaya Regency, West Java. The data provided by Tasikmalaya Disaster Prevention Agency, from January to September 2021, show that 260 hazardous events occurred in this area. Of the total disaster events, 51% of those, or 133 incidents, were landslides. This study aims to determine the susceptible zones of landslide based on existing parameters to produce a map that shows it. In addition, this study also focuses on the effect of cell size on AUC values in the study area. Therefore, several cell sizes are used to determine the effect, they are: 15, 20, 25, 30, and 35.

Methods: This study uses two methods to determine the landslide zone map: the Frequency Ratio method and Logistic Regression. The Frequency Ratio aims to determine the significant level of each factor class (Lee & Pradhan, 2007). Meanwhile, Logistic Regression produces probability values of landslides and effective values of each factor causing a landslide. The value of the landslide probability is 0 and 1; the closer to number one, the higher the level of the zone of susceptibility (Hosmer, D. W., and Lemeshow, 1989). There are 125 data on landslide events in the research area, which were divided into 80% training data and 20% validation data (Mezughi et al., 2011). The supporting parameters for landslides are lithology, slope aspect, slope, elevation, land use, rainfall, distance from fault, distance from river, curvature, and NDVI; then, a model test was carried out. This model test is obtained from the AUC graph. This test aims to determine whether the map can be applied or not.

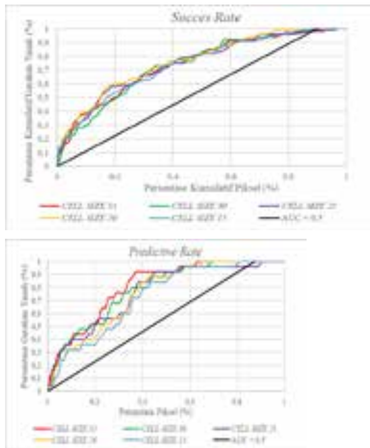
Results:



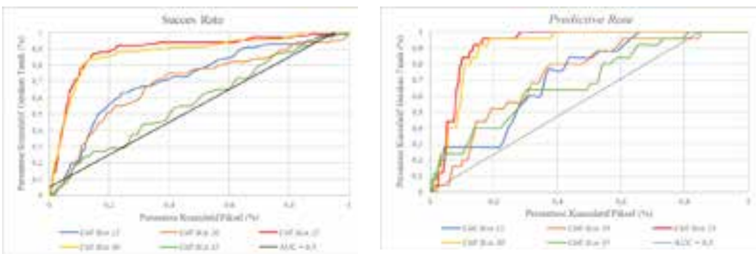
Landslide susceptibility maps Frequency Ratio: Landslide susceptibility maps based on Cell Size, (A) Cell Size 15, (B) Cell Size 20, (C) Cell Size 25, (D) Cell Size 30, (E) Cell Size 35



Landslide susceptibility maps Logistic Regression: Landslide susceptibility maps based on Cell Size, (A) Cell Size 15, (B) Cell Size 20, (C) Cell Size 25, (D) Cell Size 30, (E) Cell Size 35



Validation of Frequency Ratio



Validation of Logistic Regregression

Validation of FR and LR models: In this study, the Frequency Ratio model has an AUC value ranging from 0.73 to 0.81 (moderate model-good model). In contrast, the Logistic Regression model has an AUC value ranging from 0.58 to 0.85 (poor model-good model).

Conclusions: From the results of the AUC value, the Frequency Ratio model is included in the medium-good model, while the logistic regression model is included in the bad-medium model. Both of these models can be applied to the research area.

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P2.49

VARIABLE SUCTION AND ITS EFFECT ON STABILITY AT THE RIPLEY LANDSLIDE NEAR ASHCROFT, BRITISH COLUMBIA, CANADA

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Purpose: The primary goal of the research was to study the variable soil water content and unsaturated soil strength at the Ripley Landslide, investigating their contribution to an unseasonal displacement event in February 2017. The Ripley Landslide is one of several translational slow-moving landslides in the Thompson River Valley south of Ashcroft, British Columbia, Canada. A major factor in its stability is the seasonal changes in the river level which can vary by 8 meters throughout the year. Historically, increased rate of displacement usually occurs in the fall after the seasonal peak in river level. When the river level starts to drop, there is a reversal of groundwater gradients creating a rapid drawdown effect. However, an increase in displacement rates was not observed until February. The present study investigated the seasonal impact of precipitation and/or snowmelt as the primary trigger for the 2017 increased displacement rate. A significant component of the landslide's mass is unsaturated and stability from this part of the landslide should not be neglected.

Methods: The current study installed matric suction sensors in several boreholes along the landslide head scarp and monitored the long-term soil suction using both commercial and custom-built dataloggers. Detailed laboratory testing characterized material parameters for the near-surface till unit and identified the infiltration water source with stable water isotopes. Collaboration with the British Geological Survey was required to process data from a permanent system of electrical resistivity tomography (ERT). The "4D ERT" provided temporal plots that corresponded to soil water content, revealing early spring infiltration in the head scarp. Nearly two decades of borehole records, instrumentation monitoring, and laboratory testing was compiled into a 3D model of the landslide to provide insight into the changing stress states that led to increased displacement. The study concluded with a modelling exercise to isolate the impact of variable suction on stability.

Results: Matric suction sensors verified visual plots from the ERT that showed infiltration in the head scarp during early spring snowmelt. Soil water content changes were observed at least 1.5 meters below ground in the tension cracks. Based on the modelling study, it is evident that tension crack infiltration contributed to instability at the Ripley Landslide in February 2017. Prior to the increased rate of displacement, 0.5 inches of rain fell, which accelerated the local snowmelt. This contributed to a loss of matric suction when the river level was near its seasonal minimum. Consequently, displacement increased to a constant rate of around 2 millimeters/day. The loss of matric suction is estimated to have contributed at least 4% to the factor of safety (FOS), leading to faster displacement. This was followed by slow stabilization from suction increase and rapid stabilization from river rise, which increased the FOS by at least 11%.

Conclusions: A loss of suction due to aptly timed infiltration caused an increase in displacement after the effects of rapid drawdown had subsided. Further analysis of the conditions surrounding the event confirms that tension crack infiltration was the primary culprit for this unseasonal displacement event.

P2.50

ESTIMATION METHOD OF LONG-TERM LANDSLIDE MOVEMENT BASED ON COMBINING TANK MODEL AND LUMPED MASS DAMPER MODEL

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Purpose: The purpose of this study is to develop a method for estimating long-term landslide movement in response to amount of precipitation.

Methods: In this study, two models, a in-line three-stage tank model and a lumped mass damper model, are used. 1)The in-line three-stage tank model was used to reproduce the rainfall response of a field borehole(Sugawara,1972).Based on the amount precipitation recharge that enters the upper tank, the change in the amount of water in the bottom tank was finally modeled as the change in groundwater pore water pressure of borehole related to the calculation of the resistance of the slip surface. 2)the lumped mass damper model(LMDM), developed by Hamasaki et al.,(2016) is to describe landslide movement, in which a damper (viscous resistance) with energy attenuation proportional to the sliding velocity is added to the mass system model when considering the balance of forces loading on the sliding surface. The landsliding velocity (v) is approximately expressed as $v = (D\text{-}R) / (A \bullet Cd)$ in this model (where D: the sliding force of the landslide mass; R: the shear resistance; A: the area of the slip surface; Cd: the coefficient of viscous resistance of the sliding surface).The research site is the Kostanjek landslide in Zagreb, the capital of Croatia. Here, the following steps were considered. a) First, the changes in the pore water pressure in the borehole during the observation period from 2013 to 2018 using a tank model was reproduced. b) Next, using the actual pore water pressure in the borehole and the water pressure modeled in the tank model, each slip displacement were tried to reproduce.c) Calculated the head change in borehole with the tank model using the daily precipitation data of Zagreb city from 1961 to the present. d) A long-term prediction model for landslides was examined using the calculated results of head changes.

Results: The fluctuation in the pore water pressure in the borehole followed the change in the tank model, and the correlation coefficient was 0.90. As a result of reproducing the GNSS monitored landslide speed by LMDM based on the measured pore water pressure fluctuation, the correlation coefficient was 0.76. On the other hand, the correlation coefficient was 0.62 as a result of examining the LMDM with the movement speed using pore water pressure change by the Tank model. Both showed high correlation, suggesting the possibility of constructing a long-term landslide prediction model from meteorological observation data.Therefore, the tank model and LMDM were combined to calculate the displacement for each annual precipitation in the city of Zagreb. As a result, a displacement of 1247 mm was calculated between 1990 and 2012, which is almost consistent with the landslide displacement record.It was also found that there was a good correlation between the calculated annual precipitation and migration in an exponential manner.

Conclusions: The above analysis results show that the long-term landslide movement estimation model using the predicted precipitation can be developed by combining the tank model and LMDM.

P2.51

NUMERICAL MODELING OF LIMESTONE CLIFFS AT A SITE OF HIGH TOURISTIC VALUE

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The present contribution aims to assess the cliff stability at Polignano a Mare (Apulia, Southern Italy), by means of a combination of remote sensing techniques with the conventional geo-structural and geomechanical approaches. The municipality of Polignano a Mare is among the most attractive sites for tourists in Apulia; located along the coast, it is at the top of high rock cliffs made up by Cretaceous Limestone overlain by more recent calcarenites. The rock mass presents many intersecting discontinuity sets (structural joints and bedding), isolating rock blocks that are susceptible to failures. Detection and quantitative description of the discontinuities represent one of the most challenging aspects of hazard assessment since they play a key role in the mechanical behavior of rock masses. In addition, the soluble rocks are affected by karst processes generating large voids within the rock mass as well as weathering processes of the shallowest rock strata induced by sea spray phenomena and rainfall events, further intensifying the cliff instability. The dissolution process is enhanced by proximity to the sea, due to the mixing between seawater and freshwater. In such a context, stability analyses require appropriate rock mass characterization since the anisotropic, heterogeneous, discontinuous, and non-elastic nature of rock masses.

A comprehensive methodology for rock mass stability assessment has been carried out at Polignano in order to assess the rock fall hazard in this touristic site. The method integrates: a) conventional geological, geo-structural and geomechanical field surveys, b) remote sensing techniques, c) validation and generation of the geomechanical model, d) preliminary identification of the main kinematics, e) detection of the typical instability mechanisms, and eventually f) 2D and 3D numerical modelling in terms of both continuum equivalent and anisotropic model. The point clouds data, field surveys and laboratory tests for the physical and mechanical characterization of the rock materials have been used to build up a 3D geomechanical model. Furthermore, a first assessment of the potential failures has been performed by means of kinematic analyses, and then validated using field surveys and remote sensing inspections. The geomechanical model has been used to implement 3-D and 2-D numerical stability analyses through the construction of Finite Element Method (FEM) models (continuum and anisotropic) whose results have been compared with the mechanism failure detected in the field.

The surveys reveal the current general stability condition at the study site and that the weathering process can expose to local failures the weaker calcarenites, and the karst caves roofs as well. The failure mechanisms derived from the continuum model indicate that the failure surfaces tend to develop from the foot of the cliff, in correspondence of the sea notch; on the other hand, the anisotropic model shows small-size local failures of the overhanging sectors due to rock mass degradation. Moreover, the marine erosion action, the weathering processes and the formation of tension cracks parallel to the cliff are more likely to interact with the discontinuity systems, so that failures can develop even with low-intensity processes.

P2.52

A CATALOG FOR LANDSLIDE EARLY WARNING SYSTEMS

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Purpose: Landslide Early Warning Systems (LEWS) are designed to monitor, forecast, and analyze conditions that could trigger one or more landslides, at different scales (local, regional, national, global). The network "LandAware – the international network on Landslide Early Warning Systems" (https://www.landaware.org), created in 2020, is a multi-disciplinary international network of experts in LEWS. They work to enhance the communication and awareness about landslide risk and LEWS to all the categories of stakeholders. The main task of the WG1 "Catalog of LEWS" of LandAware is to provide a description of the state-of-the-art of existing LEWS in the form of a catalog, as well as to review the existing terminology and definitions used in LEWS. In this work we present the catalog, glossary and scoring developed by the WG1 of LandAware to help other practitioner to quick assess the robustness of their LEWS. We also include examples of the scoring in the development of national/regional LEWSs cataloged.

Methods: The glossary and the catalog of LEWS were prepared by reviewing existing scientific and technical literature describing LEWS and glossaries as well as by interviewing LandAware members. The glossary is proposed as a table listing terms, definitions, abbreviations, synonyms used for LEWS and their key references. Each LEWS is described by using 32 criteria among which 15 were selected to provide a score-based evaluation of the Early Warning System definition of the UN Office of Disaster Risk Reduction. The score system was tested by using as case studies, the Norwegian, Italian and Japanese systems, in their corresponding developmental stages.

Results: The catalog contains a list of 95 LEWS from different countries. Most of the LEWS are in Europe (46), 27 are in America, 19 in Asia, 2 in Oceania and one is worldwide. The majority of LEWS are local, or site-specific (54,7%), followed by regional ones (29,5%) with only 7,4% national. The national ones are designed to forecast three or more types of landslides (usually shallow landslides as debris flows, slides and avalanches), while the local ones for one landslide typology (mainly rockslide/rock avalanches, debris flows or rock fall). Among them, 50.5% are operational, 11 % are dismissed. The majority have been in operation for more than 10 years (46.3%). The scoring shows that most of the LEWS have a value between 10 and 15, five have a score larger than 30 and just one a maximum score of 35. The glossary contains circa 146 annotated terms.

Conclusion: A glossary, a catalog and scoring based on published English literatures have been built for the LEWS "community" and presented in its early developmental stage. This first attempt done within WG1 LandAware network over two-year of online activities, allowed to compile a catalog listing of 95 LEWS items. The catalog is instructive, provides information for comparative studies and gives a common background for describing and classifying LEWS systems.

P2.53

HYDROLOGIC SOIL MONITORING STATIONS INSTALLED IN PUERTO RICO MOTIVATED BY LANDSLIDING DURING HURRICANE MARIA

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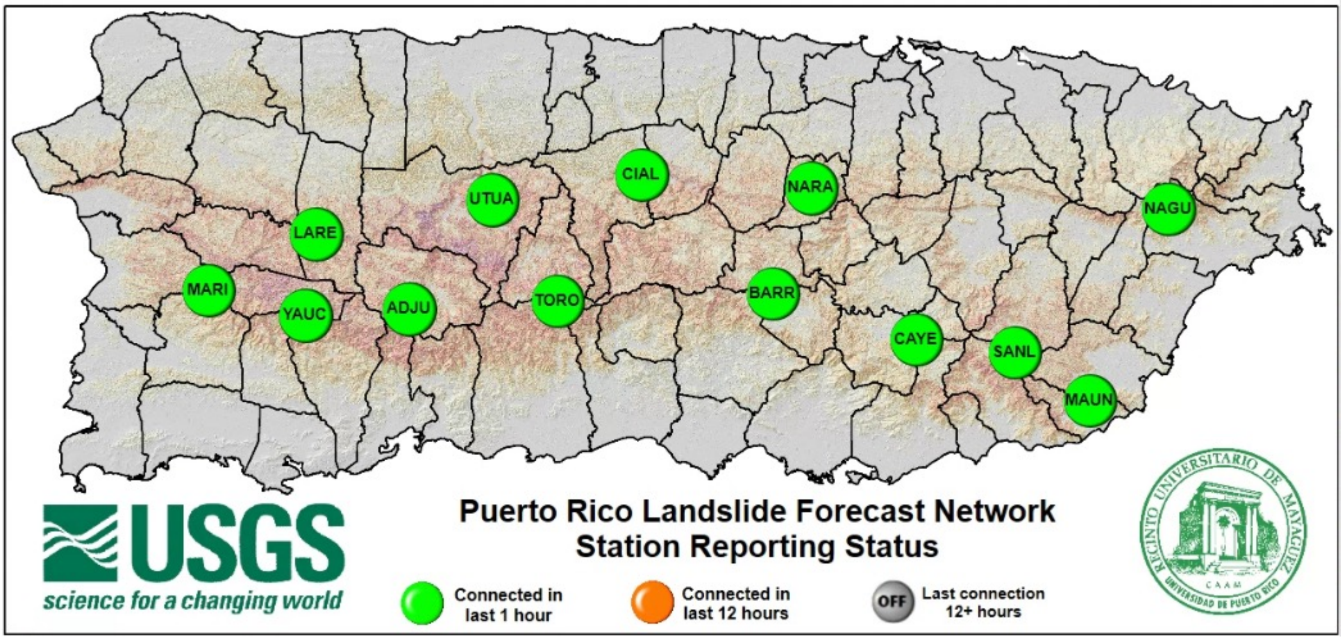
Purpose: Hurricane Maria caused widespread landsliding throughout Puerto Rico in September 2017. Hurricane Maria triggered more than 70,000 landslides and resulted in several fatalities, damage to transportation routes, utility lifelines, other infrastructure, and many homes. Rainfall-induced, shallow landslides are commonplace across Puerto Rico, even from storms that are less intense and more frequent than major hurricanes, such as Hurricane Maria. Thus, it is critical to improve our understanding of hydrologic conditions that trigger landslides during and following rainfall events in a variety of topographic and geologic settings of Puerto Rico.

Methods: To address this goal, scientists from the US Geological Survey and the University of Puerto Rico Mayagüez have installed 13 monitoring stations across the island's rugged interior to continuously monitor soil hydrologic conditions (see Figure below).



Results: These stations record rainfall, barometric pressure, soil moisture, water content, and piezometric data in near-real-time. The stations will ultimately become an integral part of a near island-wide soil moisture monitoring and debris-flow forecasting system. Monitoring data are posted in near-real time on public-facing websites.

Conclusions: This effort marks a significant step forward in mitigating landslide hazards for the 3 million residents of this US territory.

P2.54

A NATION-WIDE PROTOTYPE WARNING SYSTEM FOR ITALY COMBINING RAINFALL THRESHOLDS AND LANDSLIDE RISK INDICATORS

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Purpose: The objective of this work is the development of an innovative, fine-resolution and nation-wide nowcasting system for rainfall induced landslides in Italy. The system merges temporal predictions and spatial predictions by means of dynamic risk matrices producing hourly outputs on a municipality basis.

Methods: The nowcasting system combines two complimentary methodologies: statistical rainfall thresholds and risk indicators. A set of Intensity-Duration rainfall thresholds is defined for each of the 131 landslide-prone alert zones (AZ) in which the Italian territory is subdivided. This mosaic of thresholds provides an assessment of the probability of occurrence of landslides (according to 4 criticality levels) with good (hourly) temporal resolution but with coarse spatial resolution (AZ extension is typically in the order 103 km2). The other component of the system is a landslide risk indicator that characterizes each one of the 7906 Italian municipalities, based on the landslide susceptibility observed in the vicinity of anthropic elements. The risk indicator is a static element that can be used to increase the spatial resolution of the system (municipalities' extension is typically in the order of 101 km2) and to provide information on the expected risk scenarios. Using a dataset of thousands past landslides occurred from 2010 to present, for each AZ a dynamic matrix was built to relate, for each observed event, the risk indicator characterizing the hit municipality and the criticality level provided by the rainfall thresholds set during the day of occurrence. The dynamic matrix was calibrated separately for each AZ to obtain five possible risk levels according to the possibility of missed alarms: no missed alarms is expected in the lower risk class and only a percentage of missed alarms lower than 5% is expected in the second lower risk class.

Results: For 99 out of 131 AZs, the dynamic matrices respected the imposed calibration limits (95% confidence), while for 30 AZs a calibration was successful only with a 90% confidence. For 2 AZs affected by scarcity of data, the calibration was not successful. Considering the scale of application, we consider this outcome satisfactory and at present the improved system is being implemented in a WEBGIS interface. Additional analyses also showed that if additional landslide data are gathered and used to strengthen the calibration, the effectiveness could be improved further in a near future and the WEBGIS platform could be easily updated.

Conclusions: The proposed approach is based on the theory that the less susceptible an area is, the higher is the rainfall rate required to trigger a relevant landslide event. Conversely, a high intensity rainfall could trigger landslide even in mid or low susceptible areas, compared to a low intensity rainfall. The use of dynamic matrices combining dynamic rainfall threshold outputs with static risk indictors derived from susceptibility indexes can be effectively used to (i) increase the spatial resolution of classical regional or national scale warning systems, and (ii) allow to shift from a probability of landslide occurrence to a qualitative risk scenario.

P2.55

PREDICTION OF RAINFALL-INDUCED SHALLOW LANDSLIDES IN PYROCLASTIC DEPOSITS THROUGH HYDROLOGIC CONTROLS OF SLOPE RESPONSE TO PRECIPITATIONS

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Purpose: Rainfall-triggered landslides are widespread geohazards, often characterized by shallow and fast movements. Their occurrence is reported in many mountainous areas, and its cumulative effects are sometimes comparable to great catastrophes. Particularly, southern Apennines of Campania (Italy), commonly covered by pyroclastic deposits laying upon limestone bedrock, are subjected to recurrent shallow landslides. Different triggering mechanisms have been hypothesized, and investigation on the hydrological processes predisposing slopes to failure is still needed. This study focuses on a slope where hydrometeorological monitoring has been carried out for several years (Marino et al., 2020), and landslides recently occurred.

Methods: To assess the conditions leading to landslides, a 1000-year hourly synthetic dataset, mimicking the hydrological response of the slope to meteorological forcing, was generated. Specifically, a stochastic NSRP rainfall model was coupled with a hydrological model of the unsaturated flow through the soil cover, connected to a perched aquifer forming in the uppermost bedrock during the rainy season. Both the models had been previously calibrated based on field data. The synthetic dataset was analysed with k-means clustering and Random Forest techniques, to identify the hydrologic conditions, before the onset of rainfall events, controlling the amount of rainwater remaining stored in the soil cover at the end of rainfall, thus affecting slope equilibrium. Slope stability was analysed under the infinite slope hypothesis, considering the contribution of suction to unsaturated soil shear strength.

Results: The results show how the different hydrologic responses of the slope to precipitations, related to underground water conditions before the onset of rainfall, control slope stability. In fact, coupling antecedent conditions, expressed as root zone soil moisture and bedrock aquifer water level, with total event precipitation depth, two different landslide triggering mechanisms are clearly identified (Figure 1). On one hand, as it is typical of late autumn, low aquifer level indicates hampered drainage of infiltrating water out of the soil cover through the underlying fractured bedrock. In this case, slope failure is triggered by infiltration during large rainfall events, as almost all rainwater remains stored in the soil cover. On the other hand, when the bedrock is already filled with water previously drained from the wet soil cover, as at the end of very rainy autumns and winters, landslides can be triggered also by relatively small rainfall events. In fact, the bedrock cannot receive more water, and even exfiltration from the bedrock can occur.

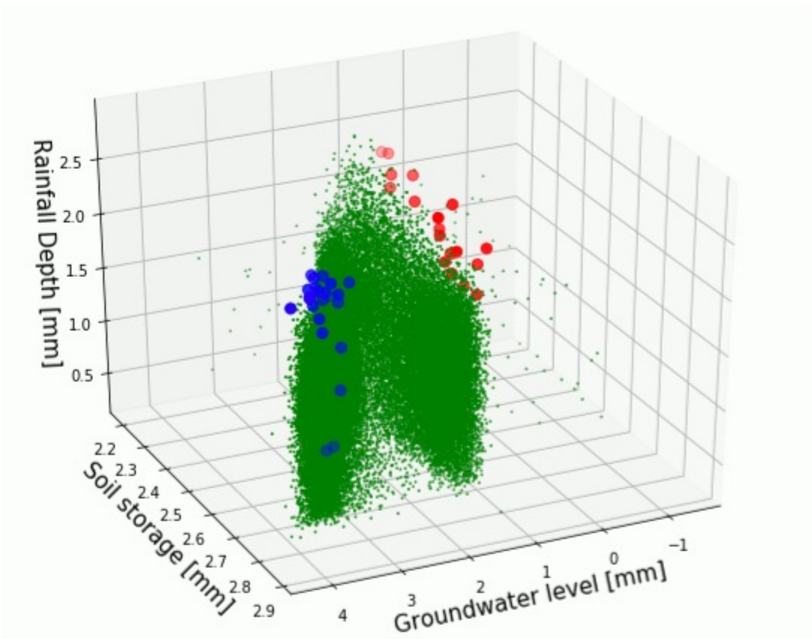

Fig. 1: Scatter plot of synthetic data in the 3D space of antecedent conditions (groundwater level and root zone soil storage) and event rainfall depth. The green dots indicate conditions not leading to landslides. The red dots represent late autumn landslides, triggered by large rainfall events with infiltrating water remaining stored in the soil cover. The blue dots indicate late winter landslides, triggered by rainfall events occurring when the bedrock is already filled with water from previous rainfall.

Conclusions: Considering antecedent conditions, expressed as root zone soil moisture and groundwater level in the shallow aquifer developing in the fractured bedrock, improves the reliability of predictions of rainfall-induced landslides in pyroclastic deposits. It also allows identifying the conditions leading to different landslide triggering mechanisms.

P2.56
NEAR-REAL-TIME SEISMIC MONITORING IMPROVES DEEP-SEATED LANDSLIDES EARLY WARNING, JIUXIANPING, CHINA

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Purpose: New technologies applied in landslides early warning are expanding rapidly, and very many research results have been achieved around the world. For example, GNSS, Satellite, Ground-Based InSAR, UAV, and laser scanning by monitoring the temporal changes of slope surface in displacement for landslide early warning. However, most of these techniques are for surface or limited point displacement change patterns, or large area-type risk forecasting, and none of them can meet the application of monitoring and early warning of geological hazards such as avalanches, rockfalls, mudflows that move rapidly in small areas and slope subsurface. Seismic technology can well make up for the deficiency of this kind of geological hazard monitoring. Seismic monitoring benefits from its real-time, remote, ability to detect ground unrest by slope surface (and/or subsurface) structure changes, and is soon being applied to landslides, rockfall, debris monitoring, and early warning.

Methods: Seismic signals generated by rock mass fall, geotechnical shear, and fractures inside and on the surface of the slope can be monitored in real-time by the seismic monitoring network. Jiuxianping landslide is an ancient deep-seated landslide with multiple slides in history, located in Yunyang County, Chongqing city in Central China. A seismic network consisting of 8 triaxial borehole geophones is installed near the sliding plane around the landslide in continuous near-real-time monitoring, besides 11 GNSS displacement monitors and rain gauges. Seismic signals received by geophones generated from the slope are integrated and classified into four classes, Slopequake at depth (includes High-frequency (HF), Low-frequency (LF), High-Low frequency (HLF), Succession of HF, Succession of LF, Succession of HLF), rockfall, earthquake, and noise.

Results: The relationship between seismic events, displacement, and rainfall can be achieved, and indicate the slope dynamic. By seismic signal Interpretation, it is possible to effectively grasp the geotechnical activity inside the slope body; (1) invert and calculate the physical and mechanical parameters of the slope geotechnical body; (2) locate the source of the signal and infer the damaged area inside the slope body; and (3) establish the dynamic stability analysis model of the slope in the time domain do early warning.

Conclusions: In the Jiuxianping landslide, the processing results and analysis have proven that near-real-time seismic monitoring improves deep-seated landslide's early warning and provides a new sight for early warning systems of landslides and other surface dynamics.

P2.57

APPLICATION OF EMPIRICAL APPROACHES FOR FAST LANDSLIDE HAZARD MANAGEMENT: THE CASE STUDY OF THEILLY (ITALY)

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Purpose: Landslide hazard management usually requires time-consuming campaigns of data acquisition, elaboration, and modeling. However, in the post-emergency phase management, time is a factor, and simpler but faster methods of analysis are needed to support decisions even in the short term. This paper focuses on the Theilly landslide (Western Italian Alps), which was recently affected by a series of reactivations, with the objective of defining an early warning system based on rainfall thresholds and to account also for the possibility of damming the Lys river, flowing in front of the slope.

Methods: While some instrumental campaigns are being carried out to support the design of protection measures, simple tools are immediately needed to assess the hazard of future reactivations and to evaluate the possibility of damming the torrent at the footslope. Therefore, state-of-the-art empirical methods were used and customized for the specific case study: a set of intensity-duration rainfall thresholds depicting increasing hazard levels was defined to monitor and forecast possible reactivations, while a methodology based on hydro-morphometric indices was applied to the case of study, to assess the possible evolution scenarios, based on the landslide volume. An empirical procedure called MaCumBA was applied to derive an intensity-duration rainfall threshold to identify the minimum rainfall conditions associated with slope instabilities. By means of a site-specific empirical calibration, the threshold was further developed into a set of three thresholds, which identify four criticality levels, each connected to an expected event scenario and a corresponding suggested countermeasure from the operational point of view. The interaction between the landslide and the river flowing at the footslope was assessed by means of a set of recently proposed empirical hydro-morphometric indices, to identify a set of threshold values of the landslide volume for which, if a landslide would reach the riverbed, the following scenarios should be expected: (i) formation of a stable dam, (ii) formation of an unstable dam, (iii) no river barrier formation.

Results: The results set three rainfall thresholds, which can be used to infer the expected scenario and consequently the most appropriate form of intervention. In the event of a landslide detaching from the slope, it is possible to make a quick estimate of the interaction with the Lys river, based on the volume of the landslide that reaches the river bed. Based on the volume, five scenarios were defined, and each one brings a different condition of the evolution of a possible river dam.

Conclusions: This work demonstrates that, when time is a crucial factor, empirical methodologies can be the most viable option to perform a quick hazard analysis and assist decision-makers. To do so, however, a rigorous site-specific calibration is required, and it should be stressed that such tools should be considered a short-term solution, to be used while more thorough analyses are carried out.

P2.58

DEVELOPING A SPATIOTEMPORAL MODEL TO INTEGRATE LANDSLIDE SUSCEPTIBILITY AND CRITICAL RAINFALL CONDITIONS. A PRACTICAL MODEL APPLIED TO RIO DE JANEIRO MUNICIPALITY

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Despite being a landscape evolution element, landslides pose a significant threat to infrastructure, property, and human life around the globe. In Brazil, this has been a major source of concern for many years. Over the last decades, especially in the humid areas of Brazil, landslide occurrences have become more frequent and catastrophic (Pelech et al., 2019). Especially in large and medium-sized cities, poorly-regulated living conditions and a progressing global warming scenario will likely increase the frequency, magnitude, and possibly damage caused by landslides (Marengo et al., 2021). On the other hand, despite the efforts of local authorities to forecast and mitigate the phenomena, not enough is currently being done in terms of preparedness for future events, especially concerning research (Dias et al., 2021).

Due to the geomorphological and climatic settings, the municipality of Rio de Janeiro (~1,200 km^2) is often affected by landslides (Coelho Netto et al., 2007; 2009). According to the Brazilian Institute of Geography and Statistics (IBGE, 2021), the municipality has 6.7 million inhabitants, of which circa 20-25% lives in the favelas. These communities, usually located on hill slopes, face diverse challenges such as poor basic infrastructure, lack of sanitation systems, and high criminality, which tend to diminish the inhabitants' awareness of potential landslide hazards. On the other hand, the municipality of Rio de Janeiro has systematically tracked rainfall data for the last decades. Such data comprises 33 stations, recording measurements every 15 minutes. Rainfall data is available for a few decades and comprise 33 stations recording measurements every 15 minutes. Also, the availability of high-resolution DTM and DEM (obtained through LiDAR with a 15 cm resolution), orthoimagery updated quasi-yearly, and a suitable landslide inventory, turns Rio de Janeiro into a promising real-life laboratory for suggesting and enhancing modeling solutions that may provide valuable tools for landslide emergency preparedness, management, and response.

Building upon the findings of Steger et al, 2022, the present research represents a joint effort to suggest a methodological framework to develop a dynamic landslide model that integrates static predisposing factors with dynamic rainfall conditions. Data-driven methods (e.g., Generalized Additive Models) will be used to establish statistical relationships between the static factors, the dynamic rainfall conditions prior to a potential landslide, and the landslide occurrence in space and time. The outcomes may be used by stakeholders to strategically prepare for potential rainfall events leading to landslides and possibly to improve early warning systems. Data collection and preparation are currently happening, and the analysis will follow. Partial results will be presented at the 6th World Landslide Forum.

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P2.59

IMPLEMENTATION OF AN OPERATIONAL LANDSLIDE EARLY WARNING SYSTEM TOOL FOR VARIABLE ANTECEDENT SOIL HYDROLOGICAL CONDITIONS IN CAMPANIA REGION (ITALY)

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Assessing hazard related to the initiation of shallow rainfall-triggered landslides commonly relies on the recognition of critical rainfall values, beyond which slope instability might occur with a significant probability. Critical values of rainfall parameters (e.g. intensity and duration) are usually recognized as rainfall thresholds which are widely used in the setting-up of Landslide Early Warning Systems (LEWSs) by the coupling with rainfall nowcasting. Empirical rainfall thresholds are based on the identification of rainfall values, representative of conditions that triggered landslide events known by chronicles, and usually do not consider some important aspects of landslide triggering (e.g. soil hydrological antecedent conditions), being also hampered by the availability of historical landslide and rainfall data. Consequently, in the last decade research on LEWSs have been oriented to estimate rainfall thresholds through physics-based modeling, consisting in hydrological and stability numerical simulations of slopes. The latter are based on a careful characterization of stratigraphic, geotechnical and hydrological features of the slope, as well as of the antecedent soil moisture status. The definition of an effective LEWS is particularly required for the ash-fall pyroclastic soil-mantled slopes of the peri-volcanic mountainous area of the Campania, which are periodically involved in catastrophic debris flows causing loss of lives and damage to settlements located along the footslopes.

In this study, an attempt to develop a LEWS for debris flows occurring along slopes of the Sarno Mountains (Campania, Italy) was carried out based on Intensity-Duration (I-D) rainfall threshold, which was derived by the coupled physics-based and the antecedent soil hydrological status modeling. A 3D hydrological threshold, based on the correlation among critical rainfall Intensity, Duration, and initial soil water Pressure head (I-D-P), was reconstructed starting from the definition of winter and summer I-D rainfall thresholds known in the literature (Napolitano et al., 2016). The latter were developed from a physics-based approach and based on the reconstruction of slope engineering geological models and field soil hydrological monitoring. In this way, a third variable has been introduced in the classical I-D rainfall threshold, in form of soil water pressure, allowing better reproducing cause-effect relationships between triggering rainfall events and shallow landslide occurrence. Moreover, to account for the decrease of soil water pressure head due to infiltration and evapotranspiration processes, time series of soil hydrological monitoring were also statistically analyzed to derive the average time-decay factor to be used to simulate values after a rainfall event. Results were incorporated in the procedure to obtain a forecasting tool for which rainfall threshold values change depending on measured and/or selected antecedent hydrological conditions.

Besides the specific case study, the proposed approach can be considered generally applicable in all cases in which the lack of past landslide inventories and/or the unreliability of corresponding rainfall records as well as different antecedent soil hydrological conditions prevent the setting of effective empirical rainfall thresholds.

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P2.60

THRESHOLDS DEFINITION FOR SITE-SPECIFIC LANDSLIDE WITH INTERMITTENT DEFORMATION IN RESERVOIR AREA: A CASE STUDY AT THE SHUIWENZHAN LANDSLIDE (CHINA)

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Purpose: Landslide with stepwise deformation often occurs under water level fluctuations in reservoir areas. Its displacement curve is multi-step, with intermittent, sudden, (quasi) periodic characteristics, as shown in Figure 1. Considering the limitations of existing methods in the early warning for this landslide type, a new method of threshold definition is developed based on machine learning.

Methods: Landslides with stepwise deformation have two states of motion, sudden deformation or staying motionless. As a result, their deformation indicators, whether displacement, rate or acceleration, have two clearly distinguishable types. Therefore, the classification algorithm is considered to analyze and mine the data of deformation and factors affecting deformation. The classical ROC curve and the current popular machine learning technology are used to define thresholds of warning indicators. The ROC curve can determine the main control factors and solo warning indicator. Machine learning algorithm can find a kind of two-dimensional thresholds and their relationship.

Results: A typical landslide with stepwise deformation in Jinping reservoir area in southwest China is selected as a case study. The landslide is located on the left bank of the Yalong River, with a volume of 15 million m3 (Figure 2). The ROC curve validated that water level factors control the landslide deformation. Based on Artificial Neural Network (ANN) and Decision tree C5.0 algorithms, a two-dimensional threshold scheme for water level factor is defined, and the inverse proportional relationship between water level and rate of water level change is established, as shown in Tab. 1, with a correct warning rate of 86.7%.

Conclusions: Due to the sudden onset of landslide moving and the sudden change of displacement rate, the early warning work focuses on the condition for the occurrence of stepwise deformation and the thresholds for the initiation of the stepwise deformation from the main control factor. The ROC curve can be used as the basic method to identify the main control factor and to define basic thresholds. The relationship between the two thresholds can be firstly established based on ANN and C5.0. This study provides reference for related cases and applications.

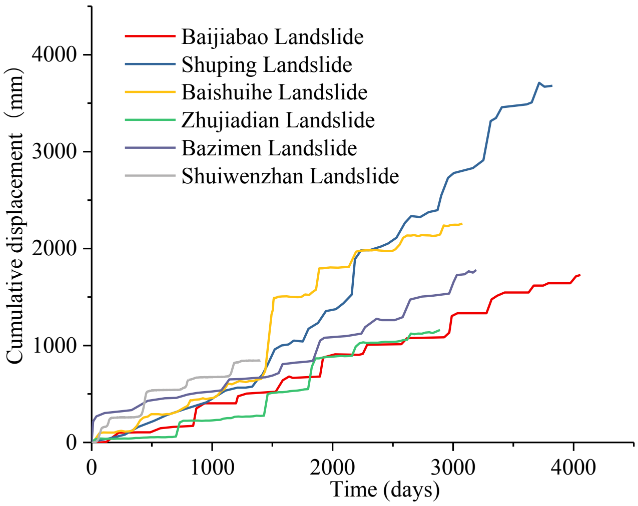

Fig. 1: Typical landslides with intermittent deformation in reservoir area.

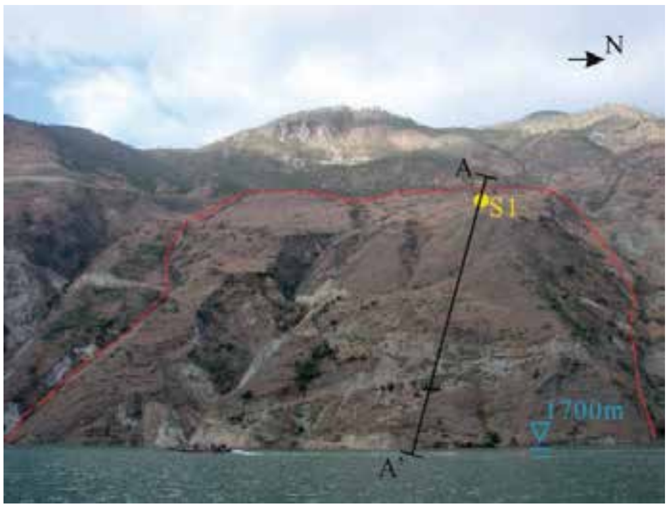

Fig. 2: Overview of the Shuiwenzhan landslide.

Table 1: Warning indexes and three threshold schemes of the landslide step-like deformation

Methods	Thresholds of water level and rate of water level change	Hit rate (%)	Error (Times multiplied by days)
C5.0	x < -0.5 & 1832 ≤ y < 1860 x < 0.5 & y < 1832	86.7	25
ANN	(x+0.3) * (y-1858)-4>0, x<-0.3 & y < 1858	83.9	190
C5.0&ANN	(x+0.5) * (y-1860)-4.7>0, x<0.5 & y < 1860	86.7	10

Note: In the above equations, x means rate of water level change, unit in m / day; y means water level, unit in m.

P2.61

IMPROVING THE OPERATIONAL EFFECTIVENESS OF PHYSICALLY BASED MODELS FOR LANDSLIDE FORECASTING THROUGH A MULTI-CRITERIAL PARAMETRIZATION OF SOIL PROPERTIES AND EVALUATION OF SLOPE STABILITY RISK SCENARIOS: THE FLORENCE CASE STUDY

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Purpose: Italy is highly vulnerable to landslides. In this scenario, landslide forecasting models play a key role in safeguarding property and population, and they must ensure high accuracy and ease of implementation in early warning systems for civil protection purposes. The triggering mechanism of shallow landslides is rigorously recreated by physically based models that use a large number of input parameters linked together by complex mathematical relationships to determine the probability of landslides occurrence. However, although rigorous, these techniques face difficulties in spatializing geotechnical and hydrogeological parameters over large areas; therefore, they are mainly employed at the slope scale. Moreover, these models do not provide immediate exploitable products for civil protection purposes because their output is a probability map, whereas for operational use it would be more useful to define risk. The main purpose of this study is to bridge this gap through an analysis of the choice of the most suitable criterion for spatializing the input data of physical models for a regional scale application, and to develop a procedure to obtain risk scenarios directly from model outcomes.

Methods: The selected study area is the Metropolitan City of Florence, for which a densely populated database of geotechnical and hydrogeological parameters is available. The model used is called HIRESSS (High Resolution Slope Stability Simulator). The modelled event starts from January to March 2016, during which 8 landslide events were reported. By means of p-value analysis, derived from several statistical hypothesis testing, two criteria were investigated for the parametrization of geotechnical and hydrological variables: one lithological and one based on pedological-landscape units, in order to account for both the lithological origin of the soils and the influence of surface erosive processes in controlling the spatial variability of input parameters. Then, an innovative GIS-based procedure based on field surveys and morphometric parameters was used to link landslide probability maps with vulnerability and elements at risk to determine a risk scenario for the case study of the catchment area of the Cesto stream (southeast of Florence).

Results: The spatialization criteria mostly supported by the analysis of hypothesis testing is the mixed one: lithological for cohesion and friction angle, pedological-landscape for hydraulic conductivity, soil unit weight and porosity. The results were validated in back-analysis, confirming the high predictive capability of the model applied with the mixed-criterial parametrization adopted. The results are in line with our knowledge of the mechanism of landslides triggering, which is particularly sensitive to cohesion and slope gradient.

Conclusions: Finally, the GIS-based risk analysis provided an impact scenario for each of the identified exposed elements. The final product is significantly beneficial for prevention and emergency management. Once calibrated, the procedure can easily be automated and replicated in other study areas.

THEME 3

TESTING, MODELLING AND MITIGATION TECHNIQUES

P3.1

SIMULATING EFFECTS OF CATCH PITS BY ANALYZING GROUNDWATER AND SLOPE DISPLACEMENT

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Purpose: In this study, the slope in the upper part of the Dalun Mountain in northern Taiwan is the test site, where data analyses of in situ monitoring and laboratory simulation are carried out. The purpose of this study is to discuss the effect of the catch pits constructed upon the slope displacement and groundwater variation within the slope.

Methods: The method applied in this study is to analyze in the situ monitoring data, rainfall amount, change in groundwater table, and displacement of sliding slope revealed by the Shape Accel Array within the slope of the Dalun Mountain. Furthermore, the relationships of these data are then correlated.

Results: The groundwater table of the W1 well drops by about 10 m after the application of the two catch pits (Figure 1), the rainfall threshold of the groundwater table rise increases and the time of returning to the normal groundwater table decreases (Figure 2). These effects cause the rainfall threshold value which triggers the slope displacement revealed by SAA-11 (Figure 3) and SAA-20 (Figure 4) to increase by at least 70%, and the creeping of the slope to decrease by 1.83-2.19 mm/year. From the results of the laboratory simulations, by comparing different rainfall amounts with or without the operation of the catch pits, it shows that the catch pits have less influence in the case of small rainfall. In the case of heavy rainfall, the catch pits significantly achieve in draining groundwater table and slow infiltration rates.

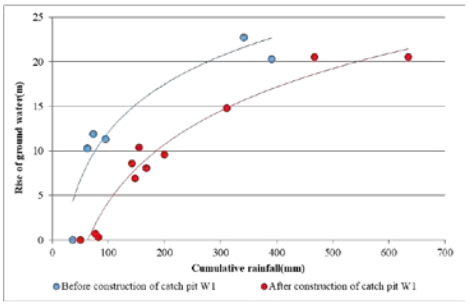

Fig. 1: Relationship between rise of groundwater and time for returning to normal groundwater table before and after the construction of catch pit W1.

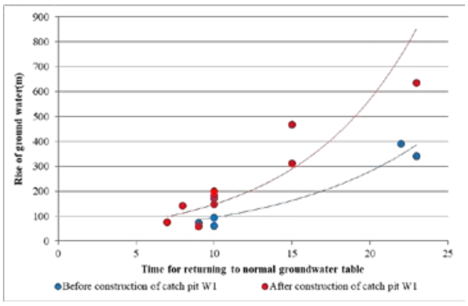

Fig. 2: Relationship between cumulative rainfall and time for returning to normal groundwater table before and after the construction of catch pit W1.

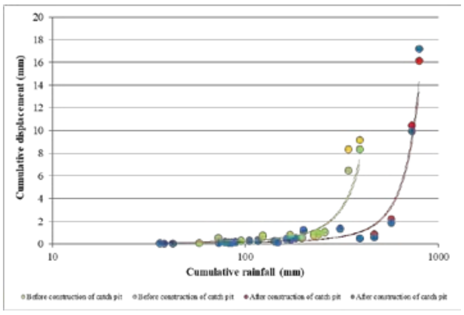

Fig. 3: Relationship between rainfall and slope displacement (SAA-11).

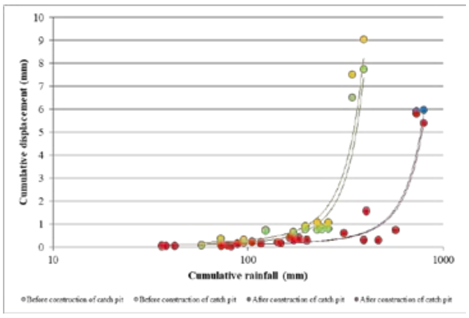

Fig. 4: Relationship between rainfall and slope displacement (SAA-20).

Conclusions: The analysis results are applied to verify that the potential displacement of the slope caused by the rainfall event throughout 2017 is close to the actual displacement revealed by the inclinometers. In this study, the types of displacement relate to the warning amount, the rainfall of the slope on the Dalun Mountain are defined as: potential slide, 280 mm; semi-accurate slide, 500 mm; accurate slide, 740 mm; emergency slide, 1350 mm. These outcomes can be a reference for slope management in the future.

P3.2
ON THE RHEOLOGICAL PROPERTIES OF SEDIMENTARY AND VOLCANIC SOILS INVOLVED IN LANDSLIDE RUNOUT PROCESSES

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Flow-like landslides are generally at the origin of sever damages and impacts to the anthropogenic environment, also in terms of loss of human lives, due to their large mobility. Both debris flows and earthflows, respectively involving volcanic soils and clay-rich materials, belong to this class of slope movements, although they occur with quite different velocities, the first being characterized by significantly larger displacement rates than the latter. Therefore, investigating the rheological behaviour of these soils and understanding the characteristics of the processes that control their triggering and propagation represent an important advancement in the simulation of these processes, as well as in the risk mitigation actions. From a conceptual point of view, the mobility of debris flows and earthflows is generally schematized according to an equivalent single-phase fluid-like material, in the framework of continuum-based non-Newtonian fluid behavior characterized by a yield stress and a suitable law of shear stress against shear rate (O'Brien & Julien 1988; Major & Pierson 1992; Pastor et al. 2002; to mention a few). However, it should be pointed out that laboratory experimental results regarding the rheological properties of the soils are often not in agreement with the observed field landslide propagation velocities.

The present contribution is aimed at presenting the ongoing work being carried out to investigate the rheological properties of volcanic soils and clay-rich flysch soils, belonging to geological formations involved in landslides in Southern Italy (volcanoclastic soils covering the slopes in Campania, flysch in the Appenine chain).

The research approach, including the experimental apparatus, and preliminary results of laboratory experiments carried out on soil samples from the aforementioned soil formations are discussed in this work and compared with both literature data available for similar soils and the typical kinematical features of observed landslide runout.

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P3.3
A 4D PHOTOGRAMMETRIC SYSTEM FOR LABORATORY INVESTIGATION OF FLOW-LIKE LANDSLIDES

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Introduction: There have been many numerical modeling schemes, including smoothed particle hydrodynamics (SPH) and material point method (MPM), for investigating landslides and their interaction with rigid barriers. However, such simulations must be validated against experimental data from scale-down laboratory models. Our objective was to develop a novel photogrammetric system to capture the dynamic land surface deformation of a laboratory-scale landslide, providing time-series information of a 3D landslide mass, including surface profile, sectional view, and dilatancy (volumetric change of a landslide body).

Methods: We proposed a stereo array consisting of six high-speed cameras to produce an image sequence at 90 fps of the landslide events. We established an automated control scheme using open-source hardware (Raspberry Pi4, Raspberry Pi Zero 2) to coordinate camera control and data retrieval, which improved both data quality and operation efficiency. We employed the Structure from Motion (SfM) technique to produce 3D point clouds of the landslide body. An in-house code developed by the authors processed the 3D point clouds to produce topography information of the flowing land mass, providing insight into the characteristics of the landslide at different stages.

Results: We performed granular column collapse experiments to simulate the process of cut-slope landslides and their interaction with rigid barriers. We explored different scenarios by varying the height of the initial column and its distance to the retaining wall. In addition, we also simulated the experimental conditions with the Material Point Method and compared the simulation results to the experimental data. Our photogrammetric system successfully generated a high-quality 3D model from the laboratory measurements, with a spatial accuracy of less than 1.5 mm compared with ground truth measurements and a temporal resolution of 90 fps. The simulation results showed good agreement with the experimental data, further validating the correctness of our system.

Conclusions: Our camera system and SfM technique demonstrated the ability to construct a high-quality 3D model in a laboratory setting. The experimental data provided a reliable dataset for validating numerical landslide simulations, increasing the credibility of simulations and providing significant benchmark data for researchers in the development of next-generation numerical schemes.

P3.4
ACCURACY OF SOIL MECHANICS LABORATORY TESTS AND ITS INFLUENCE ON THE RESULTS OF SLOPE STABILITY ANALYSIS

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Purpose: Knowledge of the shear strength of soils and their physical properties is essential for the study of landslide in the slopes. Their stability is controlled by the critical state strength or lower, even for most first-activated landslides. In the case of reactivated movements of slopes from fine-grained soils that have already been collapsed in the past, their strength is reduced by deformation in the shear zone to the residual value of shear resistance. The best way to determine the strength of soils is their laboratory testing in shear devices. The second, only indicative way, is to determine the strength of soils by estimating them based on correlation with some physical properties of soils, preferably with the plasticity index. The accuracy of the results of shear strength parameters and physical properties depends on various aspects.

Methods: We discuss specific cases of different results of the same material parameters (plasticity indexes, grading curves, critical and residual friction angles) of 5 soil samples tested in 6 different soil mechanics laboratories in the Czech Republic. We try to quantify the sources of their differences, which may depend on the type of device used, on the correctness of the laboratory test, but also on the laboratory's ability to correctly process the data of laboratory tests. The various results obtained are used for the numerical modelling of the slope stability of the landslide occurred on the important highway in the Czech Republic.

Results: For example, the preparation of reconstituted soil in combination with the systematic error of the given laboratory can provide a difference in the determination of the percentage representation of the clay fraction in the same identical soil in two laboratories up to 43 % (22 vs. 65 %). However, we also observe high differences when determining the shear strength, which on the same sample reaches a difference in values of a critical friction angle of up to 8° (20.5 vs. 28.5°). The influence of these differences is shown using a parametric study of the stability of a model slope in the geotechnical software Geo5 with the limit values of the shear strength of the same sample.

Conclusions: The results of this study have important impact on the everyday engineering geological practice. Accuracy of the simple soil mechanic laboratory tests can affect the results of follow-up research methods. The influence of the friction angle errors on the resulting values of the factor of safety (FS) of a landslide slope is not negligible at all, which can lead to unrealistic conclusions of engineering geological surveys.

P3.5

ANALYSIS OF THE INFILTRATION PROCESSES ON THE STABILITY OF PYRICLASTIC SOIL

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Every year, meteorological events trigger superficial and deep landslides on the slopes, which produce many damage and victims. To understand the processes that cause landslide and to improve the forecasting systems, the analysis of the rainfall infiltration and soil water circulation processes has a key role.

For analyzing these aspects, it is possible to make in-site experimentation or to develop laboratory analyses using physical models. In this work, some results from transient infiltration tests performed with the physical slope model are reported. The physical model consists of two connected variable tilting flume (trigger and propagation) of 1 meter wide and 3 meters in length each. It is equipped with tensiometers for measuring the suction inside the slope, pressure transducers at the bottom of the flume to measure positive water pressures, TDR system for measuring volumetric water content and laser-displacement transducers for measuring surface displacements in the orthogonal direction to the sliding plane.

Some experimental tests were conducted, using pyroclastic soil from Sarno area (Southern Italy - near the volcano Vesuvio), affected by landslide events on 5 May 1998. Deposit was composed by a layer of gravelly pumices interbedded between two layers of finer ashes (sandy loams) and was subjected to different intensities of rainfall.

The paper presents some considerations on the effects of rainfall infiltration on the stability of slopes in layered pyroclastic soils, providing an interpretation of the role played by the pumices in the affected slope area.

P3.6
POŽÁRY ROCK FIELD LABORATORY IN CENTRAL CZECHIA - NEW INSIGHTS ON ROCK BEHAVIOUR FROM MULTIPARAMETRIC MONITORING

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Purpose: Understanding the spatial variations in the rock mass is essential for delineating areas prone to rockfalls. Several attempts are also underway to characterize rock mass properties using remote sensing techniques using IRT cameras. To deepen the knowledge on this topic, a natural laboratory has been established in the former granodiorite quarry in Požáry in Central Bohemia, Czechia.

Methods: Several different monitoring methods were applied, including an in-depth borehole thermometer, meteorological station, induction crackmeters, foil tensometers, IRT camera campaigns and stable ERT profiles allowing repeated measurements. These were coupled with the analysis of rock samples´ geotechnical parameters in the laboratory (descriptive properties, dynamic elastic properties and Kic fracture toughness).

Results: The results show a high variability in rock properties and weathering rates within a small area of the rock mass. In addition, different rock material properties were found to correlate with the thermal behaviour of the rock mass during cooling (Cooling Rate Index - CRI).

Conclusions: Several different monitoring methods were used in conjunction with laboratory analyses in the Požáry field laboratory to gain new insights into the behaviour and internal properties of the weathered rock mass. Future research will focus on numerical modelling to predict the behaviour of the rock mass in a changing climate, specifically due to changing temperature gradients and precipitation patterns.

P3.7

DEFORMATION CHARACTERISTICS AND FAILURE MECHANISM OF A CUT SLOPE IN BUTUO COUNTY, CHINA

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Purpose: This paper investigates a case of cut slope failure that occurred on April 19, 2020, in Butuo County, Sichuan Province of China. The failure event has posed greatly potential safety risks to slope construction and later operation of the converter station. The main objective of the study is to understand the failure mechanisms associated with this landslide. Based on the deformation characteristics and failure mechanism of the slope, comprehensive treatment measures including temporary emergency mitigation measures and permanent stabilization works are proposed.

Methods: In this paper, according to detailed investigation of the cut slope area at field and pre-failure slope stability analysis, the corresponding failure mechanisms are thoroughly studied. Emergency monitoring, drilling, physical and mechanical experiments, and numerical simulation were carried out to deduce the prerequisite and triggering factors, and to examine the deformation processes.

Results: Based on the analysis of excavation technology and slope deformation conditions, the finite element method based on strength reduction method was used to simulate the stress-strain field of the slope, and the deformation evolution process of the slope was analyzed from the point of view of slope morphology in different periods before and after excavation. Numerical simulation results show that obvious horizontal and vertical displacements present at the front edge of the slope after excavation, and large shear strain increment is concentrated near the sliding zone. The short-term concentrated rainfall on April 13, with the daily precipitation of 21.6 mm, increased the water content in the shallow layer of the slope, leading to expansion of cracks in the unloading zone. In addition, rainwater penetrates down along the cracks to form a seepage zone, thus accelerating the softening process of rock-soil mass, which further reduces the safety factor of the slope. On the basis of the weak strength of rock-soil mass, the joint effects of the excavation and rainfall ultimately lead to the failure of the cut slope.

Conclusions: The deformation and failure of the slope mainly undergo three stages: surface creeping, crack expansion, and leading-edge deformation. The failure mode of the slope could be determined as a creep-cracking progressive slide.

P3.8

STUDY ON DESIGN AND CALCULATION METHOD OF DOUBLE ROW PILES WITHOUT COUPLING BEAM IN BINARY SLOPE

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Purpose: In order to solve the problem that Full-buried double-row piles without coupling beams are difficult to be applied in engineering practice due to difficult to quantify their mechanical characteristics and soil pressure models between piles.

Methods: This paper takes the binary slope-Gancaowan deformation as an example to establish the numerical model of double-row pile support based on the built-in soil slope analysis module of GEO5 geotechnical design and analysis software, and then the mechanical behavior of the pile inside the slope and the soil between piles is studied. Firstly, according to the rigid body limit method, the pile body stress of double-row piles is obtained, and the optimal row distance is determined by combining the internal force value of the pile body. The stress of the first and second of double-row piles are compared with that of the single-row piles in the same position, and the influence law of the stress distribution of the double-row piles is discussed, and then the calculation of the double-row piles is assisted by solving the stress of the latter.

Results: A simple new method for solving the soil pressure between the double-row piles is summarized to provide guidance for the rapid and safe construction of the slope in engineering.

Conclusions: The conclusions are as follows: under the condition that the cross - section size of double-row piles meets the specification requirements, the optimal row distance of double-row piles is 2b~4b(b is the short side length of pile section). The soil thrust of the first row piles in the double-row piles is equal to half of the sum of the soil thrust and soil resistance of the single-row piles in the corresponding position, the soil resistance of the second row piles in the double row piles is equal to half of the sum of the soil thrust and the soil resistance of the single row piles at the corresponding position. Compared with the original design scheme, it is found that the pile reinforcement obtained by the calculation method in this paper is less and the cost is lower.

P3.9

PARAGLACIAL ROCK SLOPE FAILURES CONDITIONED BY REPEATED SEISMICITY IN PRINCE WILLIAM SOUND, ALASKA

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Purpose: Paraglacial valley rock slopes in Prince William Sound, Alaska are located within a highly active seismic region and are susceptible to damage from both earthquake shaking and repeated cycles of glaciation. We hypothesize that because ice is rigid at high co-seismic strain rates, glaciers effectively buttress adjacent ice-contact rock slopes during earthquakes, reducing seismic damage. As glaciers retreat, the portion of the rock slope susceptible to seismic damage increases. Repeated earthquakes over time thus help condition certain areas of paraglacial valleys for slope failure.

Methods: In combination with field and remote mapping and rock mass characterization in Serpentine Glacier Valley, Prince William Sound, we use numerical modeling to analyze the anticipated slope response to representative earthquakes. We employed a numerical model capable of simulating both static and dynamic responses of jointed rock slopes (Itasca's UDEC) to evaluate rock mass damage. Static models incorporated rock mass structural properties, topography, and past ice elevations to simulate rock slope damage from previous cycles of glaciation. We then applied representative earthquake ground motions in dynamic simulations to assess additional damage generated by seismic loading at times of different glacier elevations.

Results: Serpentine Glacier Valley contains several large, active landslides that have been subjected to glacier cycles in conjunction with repeated seismic loading over the late Pleistocene and Holocene. Our modeling results will show the evolution of spatially distributed rock slope damage generated by individual earthquakes as well as additional damage resulting from subsequent deglaciation. We aim to simulate the observed kinematic failure modes (planar sliding and flexural toppling) found at the two largest landslides in Serpentine Valley, and show how repeated seismicity over glacial cycles generated rock mass damage that may have conditioned these areas of the slope for failure during present day ice retreat.

Conclusions: Glaciers buttress adjacent rock slopes during earthquakes reducing damage in areas of ice contact, while slopes above the glacier incur greater co-seismic fracturing. Over time, earthquake induced damage may be maximized in areas that are most often ice free, as well as at slope breaks and crests susceptible to topographic amplification of ground motion. As coastal Alaska experiences rapid glacial retreat over the next century, it is imperative to understand the added effects of seismic shaking on slopes preconditioned by previous paraglacial damage, and what regions of deglaciating valleys may be most susceptible to co-seismic failure in the future.

P3.10

A RESISTANCE MODEL CONSIDERING SLIDING-FLOW TRANSFORMATION FOR ROCK AVALANCHE DYNAMICS

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Purpose: Large rock slides usually transformed into rock avalanches and cause serious hazards. Although it has been noted that fragmentation changes the form of landslide movement (from sliding to flow), the existing resistance models rarely consider the fragmentation process, thus it is difficult to reflect the flow transformation process and mechanism, which hind the accurate simulation of the rock avalanche dynamic process.

Methods: In this study, a key physical index, the degree of rock fragmentation, is introduced to construct a correlation between the Mohr-Coulomb model and the Voellmy resistance model, representing rock slides and rock avalanches, respectively. Then, establishing a novel resistance transformation model of sliding-flow based on the fragmentation degree index. To verify the accuracy of the model, simulations were performed under the existing framework of landslide dynamic solution code based on the shallow water equation by means of a dam failure experiment and a real rock avalanche that occurred in Guangyuan, Sichuan, China, respectively.

Results: The results indicate that the present model can better simulate the acceleration process of the sliding during the initial destabilization stage than using only the Mohr-Coulomb model, which avoids the drawback of excessive resistance that hind the landslide from the inability to move. Compared with the simulation results using only the Voellmy resistance model, the present model overcomes the simulation results of overestimation of motility caused by too little resistance in the initiation phase. Using this model can better reflect the dynamic characteristics and erosion geomorphological characteristics of rock avalanches at different locations, and the simulation results are more consistent with the actual. Therefore, the proposed model can better reflect the resistance evolution law caused by the fragmentation process and better reflect the macroscopic characteristics of the disaster. The simulation results also indicate that the threshold velocity of the key parameters significantly influences the simulation results, which should be further calibrated through shearing experiments.

Conclusions: The model proposed in this study can better reflect the evolutionary mechanism of rock avalanche formation under the control of dynamic fragmentation and accurately capture the dynamic process from unstable sliding to flow. Compared with previous studies, the use of this model can improve the accuracy of potential rock avalanche extent prediction.

P3.11
A COUPLED DISCRETE ELEMENT AND PERIDYNAMIC MODEL FOR THE ROCK SLOPE FAILURE SIMULATION

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Purpose: Numerical models have the potential to predict failures in rock slopes by simulating various scenarios and analyzing the behavior of the slope under different conditions. This can help to identify potential failure modes and critical failure surfaces, enabling early warnings and proactive measures to be taken.

Methods: In this paper, we propose a novel hybrid modeling approach to simulate rock slope failures caused by crack propagation and block rupture [1,2]. Our model considers the complex interactions between individual blocks in the rock mass and the larger-scale deformation of the slope. During the initiation phase of the rock slope failure, Peridynamics is used to model joint blocks for the simulation of continuous deformation and crack propagation [3], while the discontinuous behavior around the block interfaces is considered by introducing cohesive parameters to the micro bond force relationship [4]. In the rock landslide movement stage, the discrete element method is used along with Peridynamics to model the contacts and collisions between rock blocks.

Results: This approach provides a more accurate representation of the failure process than traditional continuum- and discrete-based models. The simulation results demonstrate the effectiveness of our proposed approach in predicting failure patterns and identifying critical failure mechanisms.

Conclusions: Our model has significant potential for improving the understanding and management of rock slope instability, which is a critical issue in many geotechnical engineering applications.

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P3.12

DETECTION OF DYNAMIC FRAGMENTATION IN ROCKFALLS: IMPORTANCE OF SMALL FRAGMENTS IN FRAGMENTATION PATTERNS AND DEPOSIT DISTRIBUTION

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Purpose: Rockfall fragmentation holds outstanding significance for hazard studies and protective measure designs. At the moment, however, there is still a lack of modelling tools which also include the mechanics of rock fragmentation. The first purpose of this work is to investigate the fragmentation patterns of rockfalls and the resulting fragment size distribution within the deposit, with a focus on the behaviour of small fragments. However, natural rockfalls present a challenge due to the complex interaction between the blocks and the terrain. This often results in unknown trajectories, making it difficult to determine the velocity of impact and rotational state of the block. Therefore, a second aim of this work is to carry out an experimental campaign of fragmentation with blocks of the desired size and shape under controlled impact velocities.

Methods: Firstly, we analysed several rockfall events worldwide characterized by different amount of fragmentation. For each rockfall event, we applied image analysis techniques to map all visible blocks, to calculate their volumes, and to measure their travelled distances from the point of impact. Then, we performed fragmentation experiments both at real scale, within a quarry, and in laboratory. For the latter, we released vertically with different velocities spherical blocks made of a weakly cemented mixture.

Results: In absence of significant fragmentation, we observe in real rockfall events an increase in block size with increasing distance from the impact point or source area, in accordance with scientific literature. However, this progressive segregation of larger blocks does not hold for energetic rockfall events characterized by intense fragmentation. In such cases, small fragments show a greater distance of leap than larger ones. In the fragmentation tests, we investigated the generated fragment size distribution and their travelling distances, seeking a correlation between the exit velocity and direction of the fragments as a function of impact velocity, material property, and block and fragment masses.

Conclusions: The study allows discerning the energetic behaviour of a rockfall from the analysis of its deposit, showing a different behaviour as a function of fragmentation. This is related to the dynamic of fragmentation, as revealed by the fragmentation tests.

P3.13
THE SPITZE STEI ROCK INSTABILITY IN SWITZERLAND: MODELING AND DANGER ASSESSMENT USING A NOVEL MATERIAL POINT METHOD TOOL

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In a warming climate, extreme and unprecedented natural hazard events caused by reduced slope stability are expected to become more frequent. Most numerical methods used to model natural hazards are calibrated to reproduce historic events of a specific hazardous process. However, this calibration potentially limits their predictive capacity to simulate future, more extreme events. Hence, to assess the danger of extreme events, there is a demand for more physics-based numerical models, which are able to resolve detailed mechanical and dynamical processes.

Recently, the Material Point Method (MPM) received attention because of its capacity to simulate the coexistence of different material types as well as processes such as fracturing and multi-phase mixing or impact, for instance with water, with a unified method. In MPM the material behaviour is captured by a constitutive model, which can be calibrated with mechanical tests of the respective material. We take advantage of this promising tool to assess the danger posed by the moving rock mass of Spitze Stei, Switzerland. A release of the rock mass could directly endanger the touristic infrastructure at the nearby lake Oeschinensee. Secondary hazards could include a rockfall induced tsunami wave from the lake, temporary rise in the lake level and the entrainment of unconsolidated, saturated rock fall deposits by secondary failures, potentially leading to an immediate debris flow endangering the village of Kandersteg further down.

To assess these dangers posed by the rock instability, in our study, we model the rockfall in full scale and in three-dimension with MPM, using an elasto-plastic constitutive model for the limestone rock mass, which is calibrated with values obtained from material testing of rock samples collected at Spitze Stei. We perform calculations of different rockfall release scenarios, including different release volumes, which fail simultaneously or subsequentially, and entrainment of loose material along the path, all of which are scenarios considered to be probable on the basis of a geological survey.

We discuss and compare the simulation outcomes of these different scenarios with respect to their run-out distance, amount and location of the deposits and their danger posed to the nearby infrastructure and touristic activities.

P3.14

ROCKFALL HAZARD MITIGATION ON INFRASTRUCTURES IN VOLCANIC SLOPES USING STATISTICAL BACK-ANALYSIS. THE CASE STUDY OF GRAN CANARIA, SPAIN

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Purpose: Rockfalls on transport infrastructures are a serious hazard to users and many resources are invested in rock slope maintenance, stabilization, and protective measures. In volcanic regions, the risk of rock instabilities and rockfalls is very high due to the rugged natural slopes and origin of rock masses. The main objective of this paper is to determine the influence of geometric and material-related properties affecting rockfall motion and the effectiveness of catchment area design criteria.

Methods: The study consisted of applying a rockfall back-analysis in 11 torrential basins in Gran Canaria with different topographic configurations (slope, height, length), lithologies (soft and hard rocks) and various combinations size and shape of falling rocks. A statistical analysis of the rock stop-distances was performed establishing correlations with the different variables mentioned above.

Results: Results show that density, hardness, roundness and size of the rock blocks are material properties directly correlated with the rockfall stop-distance. However, block accumulation distribution differs with the rock hardness. Furthermore, practical maps with the block accumulation percentage are proposed for the local infrastructure planning and design tasks. These maps offer a hazard index associated with the current design of existing roads based on the relationship between the optimal stopping distance and the accumulated percentage retained along the path, complying with specific retention requirements.

Conclusions: The hazard index allows validating the suitability of existing ditches in roads and improving non-structural defense measures with reduced environmental impact and cost in volcanic regions.

P3.15

EXPERIMENTAL AND NUMERICAL STUDY ON THE IMPACT FORCE EXCERTED BY DRY GRANULAR FLOW

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Purpose: Rock avalanches are the collective downslope movement of large quantities of dry granular materials in mountainous environments. They travel quickly with a large variation in possible mass, thus posing a notable risk to human life and infrastructure. The primary approach to deal with rock avalanches is to install countermeasure structures such as rockfall prevention nets, fences, or check dams. However, the mechanical interactions between the rocks and the structures are still not fully understood, in particular with respect to changes in avalanche volume, particle gradation, and the bulk impact velocity. In this work, we systematically investigate the correlation between rock size and gradation with the impact force on a flow obstacle in experiment and discrete element simulations.

Methods: We use an inclined slope of about 1 meter height with a particle reservoir at the top to initialize a dry granular flow of Kashima sand whose mean grain size ranges from 1.8 to 5.0 mm. A load cell is placed at various distances along the runout plane to record the impact force with respect to varying initial conditions, such as particle size or total volume. Particle velocity is calculated based on particle image velocimetry (PIV). We then recreate the experimental conditions using a discrete element model using round particles. Finally, we compare the impact force acting on the load cell with the guidelines prescribed by the Japanese Sabo Technical Center (JSTC).

Results: We find that the impact force on the load cell increases almost linearly with the bulk volume. Particle size itself does not appear to affect the impact force directly, but we confirm that the impact force is roughly proportional to the square of impact velocity , which is in accordance with the JSTC standard , where is the bulk density of the flow, and is a coefficient. The JSTC guidelines recommend =1, while for our results ranges from 0.25 to 1, with the larger values occurring for larger particles. In contrast, while the overall trend is similar, the simulation results show a larger than the corresponding experimental results, ranging from 0.7 to 2.

Conclusions: We found a direct correlation between particle size, volume, and impact velocity and the impact force of a rock avalanche on an obstacle in its path. Both increased volume and higher impact velocity lead to a higher impact force, which implies more damage caused to any retaining structure.

P3.16

WEAKENING MECHANISM OF ELASTIC WAVE-INDUCED GRAIN VIBRATION IN ROCK AVALANCHE

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Purpose: Despite numerous attempts to solve the mystery behind the unexpectedly high mobility of large geophysical flows, including rock avalanche, no consensus has been reached in over a century of debate. Many hypotheses have been proposed, such as mechanical fluidization, trapped-air fluidization, self-lubrication, acoustic fluidization, dynamic fragmentation, and frictional heating. However, recent high-speed rotary shear experiments have shed some light on this issue. These experiments have demonstrated that dry dense grain flows with crushable grains are intrinsically highly mobile, quickly weakening to an low friction coefficient about 0.2, regardless of grain composition, and we have revealed the physical mechanism of this weakening.

Methods: Four different minerals' grains (quartz sands, dolomite, feldspar, and corundum) were subjected to high-speed rotary shear experiments at a normal stress of 1 MPa and a rotary speed of 2 m/s. We analyzed the acoustic signals during the shearing process and performed SEM observation on the samples after the high-speed shearing.

Results: The dry, dense grain flows that were tested demonstrated inherent high mobility. The friction coefficient of granular flow quickly reduces to a very low level of about 0.2, regardless of grain composition. At the onset of flow, the grains undergo fracturing, resulting in a distinctive fractal arrangement where the larger grains are encircled by smaller ones. This unique arrangement creates favorable conditions for generating and transmitting acoustic energy through the abrasive contact of the grains, which is evidenced by the scratches on their surfaces. The scratching action generates elastic energy (vibrations) of very high frequency in the larger grains, leading to a significant weakening of the inter-granular contacts, resulting in the flow of the grain mass similar to a massive flood (Figure 1).

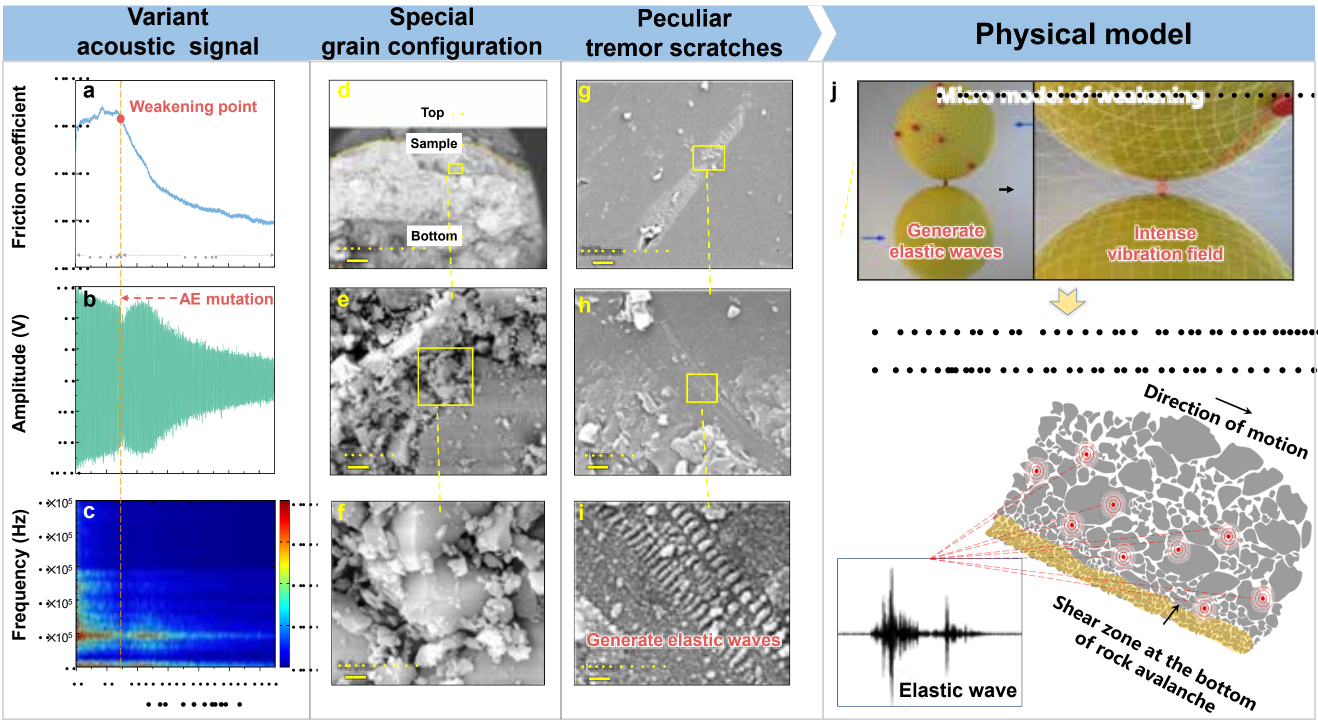

Fig. 1: Weakening mechanism of elastic wave-induced grain vibration. a-c. Evolution of friction coefficient, AE amplitude, AE frequency at 1 MPa normal stress and shear speed of 2 m/s for corundum. d-f. SEM images of cross section of sample of quartz sand sheared dry at 1 MPa normal stress and 2 m/s for ~25 m. g-i. Experimental evidence of stick-slip scratching. Smaller grains have scratched across the surface of a larger grain. j. Physical model.

Conclusions: Our experimental dense grain flows suggest that a mechanism operates at the sub-micron scale when embedded "macro-grains" are scoured by the embedding sub-micron grains. This mechanism may be a physical manifestation of acoustic fluidization, as observed in our experiments with grain flows containing largest grains of approximately 1 mm in diameter. This body-wave activated strength reduction is a significant predictable strain weakening effect (thixotropy), independent of grain material and pore fluid, but highly dependent on shear-strain rate, ultimately leading to a constant low shear resistance value.

P3.17
DELIMITING ROCKFALL RUNOUT ZONES USING REACH PROBABILITY VALUES SIMULATED WITH ROCKYFOR3D

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Purpose: Attempts have been made to automatize the delineation of rockfall hazard zones based on trajectory modelling. However, in the daily practice this delineation is mostly done by human interpretation of the simulation results and subsequent definition of the realistic runout zone for a given simulated scenario. Thereby, extreme long, low probability trajectories are generally separated from all other trajectories in the modelled rockfall runout distribution based on expert judgement, eventually supported by historical records, mapped silent witnesses (SW; i.e., deposited rocks), and other information recorded in the field. The basis provided by rockfall trajectory models for doing so is data on the number of passages per cell normalized by the total number of blocks potentially passing through a cell, which depends on the number of simulations per source cell and the number of feeding source cells. This normalized model output data can be referred to as reach probability data. The reach probability is a conditional probability depending on whether a block is released or not. At present, no standardized reach probability threshold values (RPTV) are defined for separating "realistic" from "unrealistic" simulated rockfall runouts. The objective of this study is to come up with a quantitative basis for defining RPTV by comparing reach probabilities simulated for the mapped SW. We analyze which reach probability values are typically expected in the outer range of the rockfall runout zones and quantify which block, slope and forest characteristics influence the simulated reach probabilities of the mapped SW.

Methods: We compared reach probability values (Preach) simulated with Rockyfor3D for 458 fresh SW mapped at 18 different sites in Austria, France, Greece, Italy and Switzerland and volumes ranging from 0.05 to 200 m3. All SW had estimated occurrence frequencies up to 300 years. We analyzed which block, slope and forest characteristics influenced Preach of the SW based on a linear mixed effects model.

Results: The results indicate that the limit of a realistic runout zone lies in the range where simulated Preach values are between 1% and approx. 3%. The mean Preach of the 458 SW was 1.8% and the median Preach was 1.4%. 75% of the 458 SW had a Preach ≤ 2%. The statistical model showed that the Preach values of the SW strongly depend on block volume, slope and forest characteristics. The effect of block shape was not tested. Smaller Preach values were obtained for blocks with a volume between 5 and 10 m3 passing through dense forests. The analysis of the volume distribution of SW that were not reached by the simulations indicated that these were probably block fragments. They generally had a significant smaller volume compared to the neighboring SW.

Conclusions: We conclude that RPTV simulated by Rockyfor3D lie in the range from 1.2% to 2.5% depending on the defined block volume and the encountered cumulative basal area in a forested transit zone. Where possible, the defined RPTV should be validated by field recordings of fresh SW.

P3.18

LANDSLIDE-INDUCED CASCADING PROCESS CHAINS IN THE UPPER REACHES OF THE JINSHA RIVER, CHINA

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Purpose: Large-scale landslides in high-mountain areas are likely to trigger cascading effects, characterized by long runout distances and therefore impacting distant downstream areas. Proper understanding and explicit modelling of the transformation and interaction processes involved in the landslide-induced process chains are of importance to the forward prediction of potential events. One of the main challenges in this respect is the appropriate simulation of strong solid-fluid coupling interactions, which is highly relevant in landslide-induced process chains.

Methods: In this study, a first attempt is performed to simulate the entire process chain induced by the two successive Baige landslides which occurred along the Jinsha River, China, with the multi-phase mass flow model of the r.avaflow simulation framework.

Results: Notably, the cascading effects generated by these two events cover a broad range of common hazard processes, including runout as a rock/debris avalanche and river damming, and then dam breach and the resultant flood. For the first event, we explore the evolution of the flow characteristics, the generation, propagation, and run-up processes of the impulse wave due to the landslide-river interaction, and the evolution of the overtopping and breaching of the landslide dam and simultaneous flooding. For the second event, we focus on the entrainment of the basal water-bearing material during the runout process, the second river damming, the breaching process caused by erosion of an artificial spillway, and the resultant flood.

Conclusions: Our results show that the spatial and temporal evolution of the solid and fluid phases reproduced by r.avaflow is reasonable in principle, which implies that – despite some limitations – the modelling framework based on two-phase solid–fluid mixture flows is capable of serving as a robust tool for the simulation of landslide-induced cascading process chains in high-mountain areas.

Keywords: Numerical simulation; Landslide; Process chain; Solid-fluid coupling

P3.19
LANDSLIDE IN URBANISED, DATA-SCARCE LOCATIONS UNDER CLIMATE CHANGE: HOW CAN WE QUANTIFY THE UNCERTAINTY IN THEIR ASSESSMENT TO SUPPORT HAZARD MITIGATION?

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Informal hillside communities in the humid tropics are often characterised by deforestation, unregulated slope cutting and unmanaged surface water drainage. The effect of such an informal urban expansion onto slopes, together with the potential increase of future rainfall severity due to climate change, might considerably increase future landslide activity. However, the relative impacts of these urban and climate factors on slope stability are difficult to quantify due to both a lack of soil, rainfall and landslide records within these communities (that would allow, for example, the reduction of the uncertainty around climate models' prediction), as well as a lack of slope stability models that can represent the effect of rainfall infiltration, vegetation and housing.

In this work – fully described in Bozzolan et al. (2020) – we first include in a mechanistic model (new CHASM+ software - Combined Hydrology and Stability Model) informal urban activities such as hill cutting and leaking pipes. Then, we generate tens of thousands of CHASM+ simulations that represent changing urban land cover (from forested to informally urbanised), current and future rainfall forcing, and uncertainties in slope properties (e.g., soil geotechnical parameters and initial groundwater conditions) for typical slopes in Saint Lucia, Eastern Caribbean.

Via a global sensitivity analysis of this simulation library, we demonstrate that in such locations slope cutting is more detrimental to slope stability than deforestation and poor surface water management. We then show that informal urbanisation can increase the landslide rates by up to 85% for slopes that would normally have a relatively low landslide susceptibility when naturally vegetated (e.g., slope angles of 20° to 25°). Rainfall intensity-duration thresholds for triggering landslides are then derived from the simulation library and we show that the thresholds for triggering failures in urbanised slopes are lower than those calculated for non-urbanised slopes. These new urban landslide-triggering thresholds are also comparable to those found empirically for similar tropical urbanised regions, where more landslides are observed for high-intensity, short duration precipitation events. Finally, cost-effective, or 'low regrets', mitigation actions are suggested to tackle the main landslide drivers identified in the study area.

The proposed methodology and rainfall threshold calculations are suitable for data-scarce contexts, such as when there is limited availability of field measurements or landslide inventories.

References

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THEME 4

MAPPING, HAZARD, RISK ASSESSMENT AND MANAGEMENT

P4.1

LANDSLIDE EVOLUTION IN THE UPPER MOST WATERSHED OF OHMIGAWA RIVER, CENTRAL JAPAN, BASED ON INVENTORY MAPPING AND PRECISE RADIO CARBON DATING

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Purpose: This study aims to clarify geomorphological processes on mountain slopes in humid temperate region. It shows inventory map to understand which type of geomorphological process is dominant on the slope. Chronological evolution by mass movement is also our concern. The study area is the upper most watershed of Ohmigawa river that is a tributary of Himekawa river flowing to Japan Sea along the Itoigawa Shizuoka Tectonic Line (ISTL), a Quaternary tectonic line. Northeastern Japan Arc (NEJA) and Southwestern Japan Arc are adjoining along ISTL. The Ohmigawa watershed belongs to NEJA.

Methods: Inventory mapping of landslide along the upper most streams of Ohmi Rive was carried out, using aerial photographs at a scale of 1:20000 and topographic map originated from DEM of 5m grid. Breaks of slopes which are sings of mass movements are elaboratively delineated. Authors also conducted field study along the Ohmigawa River and its sub-tributaries to understand the landslide process from facies of detritus and collect wooden substances intercalated in rocky detritus or lacustrine due to landslide blockage for radiocarbon (14C) dating. 14C of the samples were dated by Accelerate Mass Spectrometry (AMS) of Yamagata University. The result were calibrated by OxCAL v.4.4.4 and IntCal20, including data reported in the previous studies.

Results: Many landslide landforms are densely distributed in the watershed of Himekawa River area. Interpretation of aerial photographs and precise topographic maps clarified that upper most watershed of Ohmigawa River is wholly covered by various types of landslides such as deep-seated landslides, slope failures and rock avalanches except present stream beds where sever incision are ongoing. Deep seated landslide in scale of 2.6 km2 is located in the right bank of Ohmigawa river. It is marked by a landslide depression called as Kamaike on the base of the main scarp and by a chair shaped step along the valley. Relative height between the top of crown (the peak 1352m) and the river floor near Otari Hot-spring is ca 500 m. We call this large landslide Kamaike landslide (KIL). It has been subdivided by secondary or tertiary cliffs. Some blocks neighboring to river floor seems to be active, considering formation of minor fresh scarplets on the slope. A train of longitudinal mound composed of detritus continues along the upper most stream of Ohmigawa river for 2.5 km. It starts from the base of a steep arcuate scarp of which relative height is 300 m, forming a rock detritus mound. Northern part of the peak 1485 composed of Quaternary volcanic rock was therefore collapsed and rock avalanches flew along Ohmigawa valley. We call it Amakazari Highland rock avalanche (AHRA). AHRA blocked the confluences of sub-tributaries, Nakamigawa, Asamigawa rivers and formed temporal small dam lake and were quickly buried. Result of AMS dating shows AHRA occurred in 13th century. KIL occurred before AHRA event.

Conclusions: Mass movement on mountain slope is the main geomorphologic process in Neogene strata area in Japan. Time scale of geomorphologic change due to mass movement is a few hundred years only.

P4.2

DATABASES OF ROCK SLOPE FAILURES; SETUP AND EXPERIENCES FROM NORWAY

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The Geological Survey of Norway (NGU), commissioned by the Norwegian Water Resources and Energy Directorate (NVE), aim to (1) detect all rock slopes in Norway that could fail catastrophically, through mapping and hazard assessments, and (2) collect information on historic and pre-historic rock slope failures to improve understanding of present-day slope processes. This work is organized into two databases (DBs) related to rock slope failures. These DBs are important repositories of geological information designed to address specific research and societal purposes. When combined they provide complementary information that aids the understanding of rock slope failures in Norway.

The unstable rock slope DB from NGU contains information on all known unstable rock slopes in Norway, which currently includes almost 700 sites. The DB contains geological information including geomorphologic development, structural conditions, and state of activity to characterise each site. This information is used for the hazard assessment, which again is used when doing risk assessments of unstable rock slopes. The main aims of the unstable rock slope DB are to (1) serve as a national archive for unstable rock slopes in Norway, (2) execute hazard assessments for each site, and (3) inform the public through an online map service, with factsheets containing key information on each unstable rock slope.

The geological DB of past events from NGU contains geological data on historic- and pre-historic rock slope failures. It includes both terrestrial and marine landslide events, dating back to the retreat of the last ice age. It is organized in one main point for each deposit, with connected delineating lineaments, and polygons showing detachment, transport, and deposition areas. The aim of the database is to (1) collate geological information related to historic- and pre-historic rock slope failures, and (2) better understand present-day unstable rock slopes through systematic analyses of the past events dataset.

The high quantity of data related to rock slope failures requires a systematic organization of data. The presently existing DBs have evolved in line with user experience. Adaptations were made at frequent intervals and will still be necessary in the future as needs, requirements, and regulations change. The purpose of these DBs and map services is to inform society about potential consequences of rock slope failures. These DBs provide a basis for detailed research on unstable rock slopes, processes, and deposits.

P4.3
THE LANDSLIDE COUNTERACTING SYSTEM AS A TOOL FOR LANDSLIDE RISK REDUCTION AND SUPPORT FOR PUBLIC ADMINISTRATION IN POLAND

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The intensification of disastrous landslide movements in southern Poland that occurs on the turn of the 20th and 21st centuries, showed that there was a need to create a unified national system of acquiring and collecting landslide data and to raise awareness of the existence of landslide hazards. Such a system called The Landslide Counteracting System (LCS; SOPO in Polish) was established in 2006. Its basic tasks are: identification and mapping of landslides in Poland; reducing the risk of landslides and limiting the damage caused by the development of landslides. Over the years, the system grew with additional tasks: establishment and operation of monitoring system on selected landslides; identifying threats and raising public awareness of geohazards, cooperation with public administration and developing a forecasting system. The overriding objective of the Project is to reduce the risk of landslides in Poland.

Inventory of landslides for the needs of the LCS project is carried out primarily on the basis of field work (the basic scale is 1:10,000). The works are carried out using archival data and data from low-altitude photogrammetry and laser scanning (airborne and terrestrial).

The monitoring was established as a test on 60 selected landslides threatening the infrastructure. Both in-depth monitoring and surface monitoring are carried out.

In order to keep the database up-to-date, airborne laser scanning is performed for selected areas every year. Changes of landslide boundaries are identified on the basis of DTM, and then verified during field work.

For local government administration (often with the participation of the local community) a trainings and workshops are organized. They are focused on the issues of mass movements, specific of the areas in which they operate.

For the future development of the landslide forecast for the Carpathians, landslide susceptibility was determined based on selected passive factors and analyzes of the relationship between precipitation and landslide activity are currently performed.

The result of the work carried out under the LCS project is a database of landslides. Data are available in vector form and attribute form. This database is publicly available through the application. As part of the project, over 75,000 landslides have been registered in Poland by the end of 2022. It is the second (after the Italian database) base in Europe in terms of the number of registered landslides.

As a long-term development a landslide forecast concept was completed, taking into account the vulnerability of the Carpathians, precipitation thresholds and meteorological forecasts.

The effect of trainings, meetings and conferences organized as part of the LCS project is a clear increase in social awareness and legislative changes consisting in the obligation to use project data in spatial planning.

The Landslide Counteracting System has become a platform for obtaining and processing information on mass movements in Poland in order to support both government and local government administration as well as the entire society.

The system effectively supports the administration in keeping the register of landslides and spatial planning, and contributes to (as an element of) reducing the risk of landslides in Poland.

P4.4

LANDSLIDES TRIGGERED BY AN EXTRAORDINARY RAINFALL EVENT IN CENTRAL ITALY ON SEPTEMBER 15, 2022

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Purpose: On September 15 2022 Central Italy was hit by an exceptional rainfall event, with peak rainfall intensity of 419 mm in 9 hours, that resulted in widespread floods and landslides, producing damage to buildings and infrastructures, as well as twelve fatalities. Fieldwork was conducted, immediately after the event, to identify and map landslides triggered by the rainfall, to obtain information on the type and characteristics of the triggered landslides and to prepare an event landslide inventory (E-LIM.)

Methods: The area affected by the triggered event landslides extends over ~970 km2 and was delineated through a rapid and extensive reconnaissance field survey carried out immediately after the rainfall event. However, the E-LIM was prepared only inside a portion of the aforementioned area (550 km2) centered on the rainfall peak. The mapping activity involved 5 teams of researchers and lasted 20 days. The teams drove along the main and secondary roads stopping at every landslide or scenery point to map and take pictures of landslides. Google Earth was used, in the field, as a base layer to help geolocation of the landslides. All information gathered was then post-processed and organized in a tailored database.

Results: The event landslide inventory reports 1687 landslides, whose areas range in size from just a few square meters to 5.7×104 m2. Following the classification scheme by Hungr et al. (2014), each landslide was classified according to the type of material involved (rock, debris or earth) and to the type of movement (slide, slide-flow, flow and fall). Considering landslide material, 60% involve earth, 39% debris, and 1% rock. Regarding the type of movement, 65% were classified as slides, 21% as flows, 13% as slide-flows, and 1% as falls. Overall, the most common landslide type is earth slide (49% of the total inventory), followed by debris flow (17%) and debris slide (13%). Inspection of the size density (DS) map reveals that larger landslides occurred in the central part of the AOI, as opposed to the number density (DN) map, which reveals more numerous but smaller failures in the eastern sector. In general, however, both number density (DN) and size density (DS) well match the main plume of the rainfall event, corresponding to 24-h cumulated rainfall values greater than 155 mm, with DS maximum perfectly matching the rainfall intensity peak (> 248 mm).

Conclusions: Given the type of landslides that were observed in the survey, we can assert that the majority of landslides is shallow and rapid moving. Such evidence is in agreement with other similar occurrences worldwide. This suggests that exceptional/extreme rainfall events trigger mostly rapid moving landslides by inducing a sudden increase in water content and pore pressure in the uppermost soil horizons. According to climate change scenarios, more effort is needed to collect the effects of climatic extremes (such as alternating extremely dry periods and intense rainfall events) on landslide occurrence.

P4.5

DISTRIBUTION OF SHALLOW LANDSLIDES IN TROPICAL MOUNTAINS BASED ON HIGH-RESOLUTION SATELLITE DATA AND UAV SURVEYS: EXAMPLES FROM CALDAS AND RISARALDA DEPARTMENTS, ANDES, COLOMBIA

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Purpose: Modern landscape dynamics in many tropical mountains is affected by changes in land cover and variations in climatic conditions. For example, large differences in elevation and aspect increase general tendencies of changes in temperature and precipitation. Moreover, human activities related to agriculture, transport, mining, and settlements can impact local hydrological conditions but also directly transform mountain relief. These external drivers can lead to the intensification of geomorphological processes, including an increase in the number of shallow landslides, which in some cases can threaten human life and infrastructure.

Methods: This study combined field-based and remote sensing data to map the distribution of landslides in a landscape representing a tropical mountain environment strongly affected by human presence. Study area includes four sites in Andes, Colombia in departments of Caldas and Risaralda: Salamina, Santuario, Santa Rosa de Cabal, Florida. Time series of high-resolution satellite imagery (Ikonos, WorldView, Pleiades) from 2000/2003, 2013/2014, 2019/2020 were used to identify the location of landslides and develop a spatial database. Remote mapping was verified during the fieldworks in 2017, 2018, and 2019. In addition, very detailed UAV data were generated for selected landslides to obtain their geomorphological characteristics. In the last step, frequency ratio modelling was used to investigate the relationship between topographical and land cover factors and landslides distribution.

Results: In total, we mapped more than 900 small landslides characterised by an area from 102 m^2 to 104 m^2. Most of the landslides were located in cultivated landscape (pastures, farms, plantations) or along local roads.

Conclusions: Our results indicated four potential scenarios of landslide activities: (1) intensification of landslide processes and increase in the landslide area; (2) active landslide, but stable in terms of dimensions (2) activation of new landslides; (3) deactivation and vegetation succession. Most of the activation of new landslides and intensification of existing ones were related to direct human terrain modification, mainly developing new roads or repairing existing ones. The research was funded by the Polish National Science Centre, Poland (Project number 2015/19/D/ST10/00251)

P4.6

ASSESSMENT METHOD TO THE POTENTIAL LANDSLIDE BARRIER LAKE BASED ON THE GOEMORPHOLOGICAL CHARACTERISTICS IN KAOPING RIVER, SOUTHERN TAIWAN

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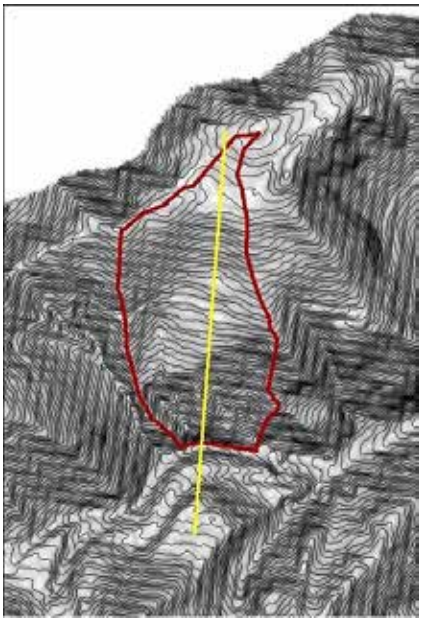
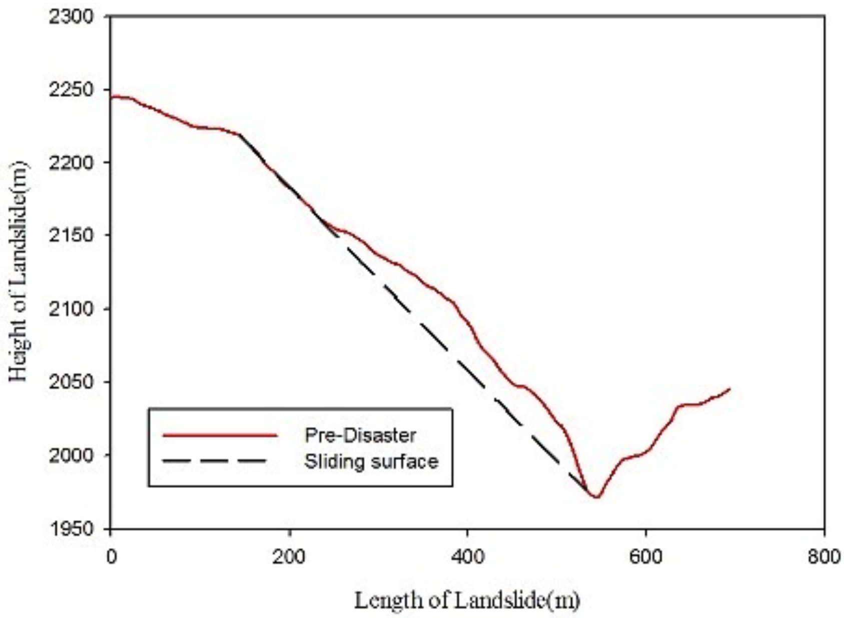
Purpose: The spatial assessment method of the potential landslide barrier lake (PLBL) based on geomorphological characteristics has been developed to predict the possible location of the landslide barrier lake in the watershed to provide information on the early warning of landslide prevention.

Methods: This research collected 25 events of the landslide barrier lake (LBL) in the Kaoping River of southern Taiwan. The terrain features of 20 LBL events were investigated to explore the topographic conditions of the prone blockage location at the river channel. The landslide failure plane model SLBL (Jaboyedoff et al.,2019) was tested by the actual dammed events and then developed an estimation process for the landslide volume. The method proposed by Tabata et al. (2002) estimates the minimum volume VDmin of landslide barrier lake was utilized to calculate the minimum volume of the submerged LBL dammed mass in the river channel.





Results: The representative topographic features such as "main scarp" and " homologous gully " are used as the indexes to predict the location of the potential landslide barrier lake. Found the potential site of LBL, the longitudinal profile estimated a quadratic parabola curve as the sliding plane of the slope starting from the main scarp to the point of the foot inside the landslide mass. The cross-section of the sliding body was also estimated as a quadratic parabola curve beginning on both sides of the lateral scarp or homologous gully. Reviewing the property of the length and width of LBL events, it can be roughly inferred that the larger the landslide length and width, the higher the height of the landslide dam. The runout distance of the mass movement is estimated by the equivalent friction method using the above estimation method to achieve the barrier dam volume, dam height, and dam bottom width. Eventually, judge the estimated PLBL volume and the minimum requirement barrier dam volume to determine whether it will form a landslide barrier lake.

Conclusions: This study is an assessment method for the PLBL location through the procedures: determining the sliding mass boundary by microtopographic characteristics, calculating the landslide mass volume, calculating the minimum requirement of dammed volume, and comparing both volumes. This interpretation method can be a reference tool for determining the potential location of LBL to enhance disaster prevention work.

P4.7

LANDSLIDE SUSCEPTIBILITY EVALUATION USING THE INTEGRATION APPROACH OF PHYSICALLY BASED ANALYSIS RESULTS AND DATA-DRIVEN METHOD

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Purpose: Various landslide susceptibility analysis methods were used to predict landslide occurrence. Commonly, landslide susceptibility analysis methods can be classified into data-driven and physically based approach according to their methods incorporating conditioning factors and models. Data-driven methods evaluate the probability of future landslides by evaluating the statistical correlation between landslide inventories and conditioning factors. In contrast, physically based methods evaluate slope stability by considering landslide occurrence mechanism with geotechnical properties of the ground through physical slope model. However, the physically based approach uses only limited factors such as slope angle and strength parameters but does not consider other important conditioning factors such as forest types, curvature and TWI. In this study, the physically based analysis is combined with a data-driven model to consider the influence of various landslide conditioning factors and so improve landslide prediction accuracy.

Methods: In this study, physical slope model coupled with transient hydrogeological model to evaluate pore-water pressures as a consequence of time-variant rainfall effects. This approach has an advantage that the change of slope stability can be estimated on the basis of rainfall amount, which the traditional data-driven approach cannot acquire. Then, the probability of failure is then calculated using Monte Carlo simulations (MCS) to accommodate the uncertainties involved in the procedure of data acquisition and analysis. The analysis results were provided as spatially distributed landslide susceptibility map and subsequently, combined with data-driven approach. In this study, multi-layer perceptron (MLP), which is an advanced deep-learning model, was used to combine to physically based landslide susceptibility analysis.

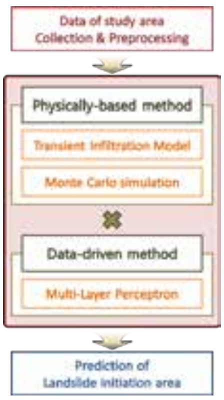

Figure 1: Flow chart of landslide susceptibility using integration approach.

Results: The improved susceptibility map was created by combining the results of physically based model analysis with those of MLP model. This procedure can be effectively performed since the two analysis results were obtained as probability values between 0 and 1. The performance of the combined method was compared with the conventional physically based method using the accuracy and error rates. The error rate and accuracy results showed that the combined results which considered the influence of various conditioning factors were significantly improved. In particular, the analysis results of the previous approach had a substantial dependence on geomorphological factors such as slope angle, but this influence was reduced in the combined model.

Fig. 2: The susceptibility map using (a) physically based model, (b) data driven model, (c) combined physically based and data driven.

Conclusions: In this study, physically based and data driven approaches were combined to improve the performance of the conventional landslide susceptibility analysis by incorporating the influence of various landslide conditioning factors. Since the analysis results of the conventional physically based model were heavily dependent on the geomorphological properties, the data driven model, which is capable of considering various landslide triggering factors, was combined to improve the accuracy of these analysis results. Accuracy, error rate, and AUC statistic clearly indicate the improved performance of the combined model proposed in this study.

P4.8
DETECTING LANDSLIDES AND FLASH FLOOD EVENTS IN DATA-SCARCE REGIONAL CONTEXTS: A METHODOLOGY DEVELOPED OVER THE EAST-AFRICAN TROPICS

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Rainfall-triggered landslides often occur in a compounding/cascading manner together with flash floods. Establishing regional-scale inventories of landslide and flash flood events together is crucial to understanding their behaviour in both space and time, particularly in the tropics, where these geomorphic hazards (GH) are under-researched, and impact is disproportionally high. Recently, an increase in focus is seen on the use of machine (ML) and deep learning (DL) methodologies for accurate detection of GH. These methodologies however, have in common that they rely on accurate information on either the GH location (training samples) or the GH timing (pre- and post-event imagery), making them practically unusable in unseen areas without any information on GH occurrences. Here, we develop a methodology that allows for regional multitemporal GH event detection, providing both location and timing of GH events without any prior knowledge on GH event occurrence. We use a pixel-based methodology that uses the cumulative difference from the mean of a multitude of spectral indices. Our methodology uses the open-access, relatively high spatial resolution (10m) Copernicus Sentinel-2 time series and creates a map that identifies impacted pixels and their related timing for each tile. We are able to identify (compounding/cascading) landslide and flash flood features that occur in different parts of the time series, in different landscapes and containing different compositions (size distribution/ landslide to flash flood ratio). Our methodology to compile regional-scale inventories is calibrated and validated over the western branch of the East African Rift, a tropical region stretching over more than 1000 km. Our methodology works in various landscapes, shows potential for transferability and allows to detect GH events in previously unseen areas. It is highly optimized in terms of computation time allowing to process large regions of interest, within a relative short time span.

P4.9

GIS TOOLS FOR DEBRIS FLOWS RUNOUT ASSESSMENT THROUGH GEOMETRIC APPROACH

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Purpose: The hazard maps for debris flows often provide information about events already occurred (inventory maps) and/or on detachment areas (susceptibility maps). Runout maps that offer an estimation of the propagation areas of debris flows starting from known potential initiation areas are very rare. To fill up the gap, this work concerns a runout GIS toolset, developed as an easy-to-use and efficient solution for the propagation assessment of debris flows in wide area analysis. The application is conducted by exploiting the potentiality of the GIS tools for data processing that allow the automation of several step of the analysis.

Methods: Peloritani mountains in the Messina province (Sicily, Italy), as a data-rich river basin with a huge number of shallow landslides, is used to demonstrate the rationale, functions and capabilities of the runout GIS tools. The dataset consists of about 800 debris flows surveyed through the observation of several post-event (2007, 2009 and 2012 events) images. The analysis is based on the geometric approach, typical of empirical methods, in which one or more dimensional characteristics of a debris flow are related to the maximum runout. For each of the observed landslides, the detachment area, the runout path, and the toe point were drawn manually. Instead, the top of the main scarp, the slope break point along the path and the volume of the mobilized material were identified automatically through the application of all the implemented GIS tools. The volume was calculated using a soil depth map produced following the GIST method. The dataset was divided into two equal parts, one half of which was used in the learning phase and the other in the validation phase. The learning phase was aimed at identifying the site-specific parameters for each of the functions used. In the validation phase, starting from the observed polygons, the drop water paths were automatically identified and subsequently, by applying each of the functions, the propagation distance was estimated and the toe point located.

Results: The reliability assessment was conducted through a comparison between the observed and the estimated runout value. The results demonstrate that the implemented GIS tools largely facilitate the runout analyses in wide area assessment that require the execution of numerous algorithms in sequence to achieve the identification of the landslide path and the runout distance from several potential initiation areas. In this framework, starting from a debris flows susceptibility map, the geometric approach is especially useful to implement tools devoted to regional planning and (pre)early warning system design.

Conclusions: Despite the extreme simplification of the dynamic of the phenomena under investigation, the geometric approach can provide prediction of the extent of the landslide propagation with good reliability. Moreover, it can successfully support decision-makers and are consistent with more recent guidelines for landslides risk assessment.

P4.10

DEBRIS FLOW MODELLING FOR FLOOD RISK MANAGEMENT PLANS

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Purpose: Among the geomorphic processes occurring in steep headwater basins, debris flows can be regarded as one of the most hazardous phenomena due to their magnitude, routing velocity and high occurrence rate. They play a major role in natural hazard management because of their destructive power and high socio-economic impacts. These phenomena are frequently observed in the Italian Alps and in similar geological contexts all around the world (Gregoretti et al., 2019). In accordance with European and national legislation, debris flows should be included in Flood Risk Management Plans (FRMPs) that are developed by River Basin Districts to assess, manage and reduce flood risk at river basin scale.

Methods: For its 2021-2027 FRMP, the Eastern Alps River Basin District (ADB-DAO) has developed a multi-step procedure to evaluate and map debris flow hazard. Firstly, debris-flow-prone channels are identified on the basis of historical records, photointerpretation, GIS-based analysis and field surveys. Secondly, debris flow phenomena are simulated with a bi-phase, moving-bed GIS-based cell model (DFRM) developed by TESAF (Bernard et al., 2019). High resolution digital terrain data and topographic surveys of structures such as bridges and weirs are used for debris flow routing. Specific modelling scenarios are defined to simulate channel avulsion and bridge obstruction phenomena. Finally, debris-flow hazard maps are built using a magnitude-probability matrix (Heinimann, 1998) linking hazard level to the intensity and frequency of expected debris flow events.

Results: The procedure was applied to small (about 0.5 to 10 km2) catchments in Northeast Italy with moderate to high vegetation cover and sediment production, limited anthropogenic pressure upstream of alluvial fans but significant channel modification and human presence on fans. Model parameters were calibrated by matching observed and simulated phenomena in comparable basins (Gregoretti et al., 2018). Interactions between debris flows and man-made structures play a major role, generally producing larger debris-flow affected areas and higher hazard levels. Model outputs were found to closely match field and historic evidence of past events.

Conclusions: Detailed hazard maps based on debris flow modelling provide crucial information for hydrogeological risk assessment in mountain areas. Shared, evidence-based methods are required to ensure a consistent implementation of risk management, promote the protection of human health and safety and guide sustainable urban and rural development.

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P4.11

USING PYTHON TO AUTOMATICALLY DRAW THE LANDSLIDE SUSCEPTIBILITY MAP OF EARTHQUAKE-INDUCED LANDSLIDES - A CASE STUDY OF THE CHI-CHI EARTHQUAKE LANDSLIDE INVENTORY

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Purpose: Taiwan is located in the Circum-Pacific Belt, where earthquakes occur frequently throughout the year. With numerous active faults, there is always possibility of major earthquakes. Statistics show that, in addition to the earthquake itself, landslides caused by the earthquake can also result in significant loss of life and property. Therefore, it is important to quickly and accurately identify areas at the risk of landslides during an earthquake, not only for the evacuation of residents but also for rescue operations by emergency personnel.

Methods: This study aims to use Python to produce near real time landslide susceptibility maps, reducing the need for time-consuming manual data processing. According to the model developed by Professor Chyi-Tyi Lee in 2014, which employs logistic regression to calculate the susceptibility based on eight factors including slope, aspect, lithology and so on. This study adopts Chi-Chi Earthquake landslide inventory and seismic signal to build logistic regression model to simulate occurrence of landslides. This logistic regression equation is applied to obtain the landslide susceptibility values for entire Taiwan.

Results: The analysis results show that the area under the curve of ROC (AUC) of this model is 0.906. There is another index in confusion matrix which is called recall is 0.857, meaning that 85.7% of landslides are predicted. The process of the aforementioned steps and the export landslide susceptibility map can be achieved within few minutes. Additionally, the study applies a new conceptual model of production: utilizing Arias Intensity to divide the data into a few groups and calculate the logistic regression model under different Arias Intensities. The goal is that this method can identify which factors have a significant impact on landslides under different Arias Intensities.

Conclusions: In the future, the goal is to select the most suitable model and convert it into an automatic program. When a major earthquake occurs, remote sensing technology will be used to collect information of landslides and seismic signals from strong motion stations. Logistic regression analysis will be conducted to generate a model, then after combining the technology of aftershock prediction, an aftershock intensity map will be generated. By inputting this information into the previously calculated model, the distribution of potential landslides caused by aftershocks can also be identified, so that to reduce the potential for secondary damage.

P4.12
PROPOSING A TOP-DOWN DATA-DRIVEN FRAMEWORK TO IMPROVE NASA'S LANDSLIDE SITUATIONAL AWARENESS SYSTEM

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Purpose: This work pinpoints a discernible paradox in Landslide Hazard Assessment for Situational Awareness (LHASA): 1) simplicity in avoiding the intrinsic uncertainties stored in each part cascade through the entire computational process and diminish the value of a more inclusive and integrated analysis, and 2) including enough accessible and achievable components with a controlled level of uncertainty to provide a representative forecasting map of landslide occurrence. The latter issue would be surmounted with a Top-Down strategy.

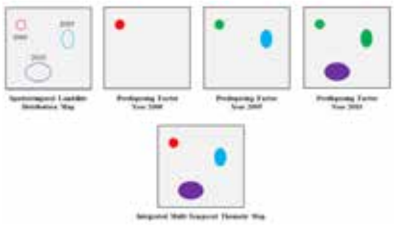

Fig. 1: A schematic procedure of making an integrated multi-temporal thematic map.

Methods: This research tackles the main shortcomings of the current LHASA framework of NASA, based on which a conceptual model for landslide hazard assessment and forecasting is proposed. We believe that the paradox between the simplicity and complexity of a global landslide awareness system would be settled by a Top-Down strategy in which the global scale can operate on a more simplistic framework (the current version), and prediction deficiency hotspots will be subjected to more detailed analyses (Figure 2).

Fig. 2: A three-step framework proposed for landslide awareness system of NASA/LHASA

Fig. 3: A proposed framework for assessing Land Cover Change Rating System (LCCRS)

Results: The computational unit should align with landslide morphological characteristics (i.e., pixel-based vs. slope units). More predictors can be involved to get a better spatial differentiation of the hazard classes, especially in areas with limited landslide datasets, including DEM-derived morphometric indices. Different susceptibility maps and, subsequently, different hazard maps should be generated based on the type of movement, while depth-wise classification can be used for rainfall threshold identification. We propose "integrated multi-temporal thematic maps" for each predisposing factor in order to consider the status of the predisposing factors at the time of occurrence (Figure 1). Ensembled or solitarily used machine/deep learning models with k-means cross-validation techniques for data sampling and adopting a multi-metric performance sieve to opt for the superior model is also proposed for susceptibility assessment. In addition to the hourly accumulated rainfall (3 to 72 hours) obtained from TRMM data, different rainfall characteristics should be considered, such as IDF curves, Antecedent rainfall characteristics, and Inter-Event Time Definition. Copula functions are also helpful in constructing non-linear joint distribution functions of different parts of the proposed framework (e.g., IDF, susceptibility-rainfall, IEDT, and Value at Risk for uncertainty analysis). More attention should be paid to the near-miss event, especially in making a landslide inventory catalog. Since most of LHASA's inventory is based on media, a team should be designated to purify the landslide catalog from de facto data. A Land Cover Change Rating System (LCCRS) should be integrated into LHASA's framework to immediately detect anomalies in land cover (i.e., sudden changes in land use/cover) (Figure 3).

Conclusions: The proposed Top-Down technique allows LHASA to adopt a more flexible form in predicting and finding the anomalies. Adding more elements into the system should always be done at a controlled level of uncertainty, a big part of which LHASA has been oblivious.

P4.14
THE NATIONAL IDROGEO WEB PLATFORM FOR LANDSLIDE DATA COLLECTION AND SHARING

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Purpose: The national IdroGEO web platform allows the navigation, social sharing and download of data, maps, reports of the Italian Landslide Inventory - IFFI, national hazard maps and risk indicators. IdroGEO is a tool for communication and dissemination of information to support decisions in risk mitigation policies, land use planning, preliminary design of infrastructures, prioritization of mitigation measures, management of civil protection emergencies and environmental impact assessment.

Methods: IdroGEO is an interactive and collaborative web mapping application, and addresses three categories of functionalities: viewing, editing, and analysing. In addition to the basic tools (zooming, panning, turning on/off layers), it provides tools for queries and production of reports, uploading of new information (e.g., reporting a new landslide), sharing content on social media, visualization of multimedia content on landslides, up to the possibility of performing spatial analysis (e.g., scenario calculation). The main strengths of the platform are ease of use, the accessibility with different types of devices (smartphones, tablets, desktops), "mobile first" approach, multilingual interface (IT, EN, FR, DE), interoperability (Rest API, OGC Services), dynamic extraction of information on the area displayed on the map providing immediacy to the content. The main categories of users are decision makers, land use planners, rail and road companies, professionals, and citizens. Dissemination of information from government to citizen contributes to increase risk perception, awareness, and informed behavior about landslides and floods in Italy and to promote the resilience of society.

Results: IdroGEO simplifies and increases the efficiency of landslide data collection. Online landslide updating services are available for IFFI regional officers allowing editing of point, linear and polygonal geometries, and collection up to 144 parameters into the landslide form, enabling multi-user acquisition and storage of large amounts of data into the national inventory. Professionals can "report a landslide" locating a point on the map and easily entering its main information, photos or videos.

Conclusions: The IdroGEO web platform will be enhanced with new tools and services to support landslide mapping: 3D map viewer, tools for the analysis of site parameters (e. g. slope angle, lithology, land use), and integration of Satellite SAR data services, in the framework of Geosciences Research Infrastructure funded by Next Generation EU. The National Database of Landslide in situ Monitoring Systems (NDLMS) and User Interface (UI) will be implemented for the management of near real time monitoring data. The IdroGEO platform will guarantee over time data and interoperable mapping services on landslides, according to FAIR data principles.

P4.15
MAPPING RELEASE AND PROPAGATION AREAS OF PERMAFROST-RELATED ROCKSLOPE FAILURES IN THE FRENCH ALPS TO IDENTIFY HOT SPOTS FOR HAZARD ASSESSMENT

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High mountain environments are particularly sensitive to rising air temperature, causing significant landscape changes. Rock wall permafrost degradation sometimes led to rock slope failures while retreating glaciers leave room for new lakes to form in glacier bed-overdeepening, a source of potential cascading hazards that can spread over long distances down the valley. These emerging hazards pose a new threat to mountain population and it is necessary to anticipate these future changes and their possible consequences. The aims of this study are to characterise the triggering and propagation mechanism of rock slope failures, and to propose a mapping approach of potentially unstable permafrost-affected rock walls and possible runout distances if failure occur at a regional scale. This information is crucial for identifying hotspot that require subsequent hazard assessment, particularly in light of the ongoing climate change.

To do so, we used an inventory of 1389 rock slope failures (volume > 102 m3) recorded in the Mont-Blanc massif from 2007 to 2019 and determined the topographical and permafrost conditions that are most prone to their triggering using a digital terrain model and a permafrost map. These conditions are used in a multi-criteria GIS approach to identify potential unstable slopes at the French Alps scale. Then, the potential release area map is used as input to map the runout of potential events, using a propagation model based (RockavELA) on a normalised area dependant energy line principle.

Three propagation scenarios are proposed, fitting the propagation characteristics of another rock slope failure database containing 3497 events observed throughout the European Alps with heterogeneous propagation substrates, and merged with 48 additional events from the French Alps high mountains. RockavELA reproduced runout extent of 20 high mountain rock slope failures with < 50% of frontal and lateral error. Output maps show little sensitivity to the propagation scenarios (< 25% difference between the high and low propagation scenarios).

The resulting maps of release and propagation areas could be used to point out human assets (mountaineering routes, high mountain infrastructure, tourism areas) and lakes which could be impacted by rock slope failure hazards. In this communication we will present this work and show how it can be used to identify potential hotspots for a regional hazard assessment.

P4.16
STUDY OF ESTIMATION METHODS AND DEVELOPMENT OF A SYSTEM FOR ESTIMATING AREAS AT HIGH RISK OF SEDIMENT TRANSPORT

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Purpose: After major landslide events, rapid damage assessment is conducted to determine the scale of the landslide and to delineate potentially hazardous slopes and streams that may cause adversarial events in the near future. However, field responders do not have adequate information for self-protection. This issue cannot be overlooked. Therefore, we developed a system to evaluate the risk level of streams affected by landslides based on pre-known disaster cases by way of pattern matching of topographical and geological information lest any unwanted secondary disaster may occur.

Methods: 1. Analysis of the relationship between rainfall and collapse. We organized the distribution of collapses over the past decade in relation to rainfall history, topography, and geology, and analyzed the factors that influence the occurrence or non-occurrence of collapses. The analysis was conducted in approximately 1 km2 units where the precipitation analyzed by radar-AMeDAS was organized. 2. Estimation of the extent of debris flow using a database of disaster cases. For debris flows, we compiled a database of the watershed area, riverbed gradient, geology, and debris flow inundation width of the stream where the debris flow occurred. Furthermore, we developed a system that can easily evaluate the extent of debris flow inundation by specifying the point to be evaluated, calculating the watershed area and riverbed slope from the DEM, and citing a database of disaster examples with similar topographical conditions. The system was built to be used on mobile devices for use by surveying responders in the field.

Results: A statistical relationship was found between the annual exceedance probability and the collapse rate for the largest rainfall in the past 10 years. For the newer geology, there was a clear tendency for the collapse rate to increase with increasing annual exceedance probability of rainfall. On the other hand, older geological features showed a slower increase in collapse rate in response to rainfall. In addition, we conducted a field test of a simple system for estimating the extent of debris flow inundation and confirmed that the system could output the results within a few seconds of whether the area was included in the inundation zone of a debris flow. Furthermore, the results of the application at the disaster site confirmed that the inundation widths were generally consistent when the geology was considered in the area determination.

Conclusions: The protection of front line responders and engineers is of imminence. It is strongly hoped that the results of this study will swiftly be adopted to make better and smart response in the first phase when risk information on landslide and sediment transport is non-obtainable.

P4.17
UPDATE LANDSLIDE SUSCEPTIBILITY MODELLING - A NEW FRAMEWORK TO COMPARE AND UPDATE A REGIONAL SCALE LANDSLIDE SUSCEPTIBILITY MODEL

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For nearly ten years, the Geological Survey and Spatial Planning Unit from the Regional Council of Lower Austria uses a landslide susceptibility map generated by a LSM (Landslide Susceptibility Model) to guide and enhance multiple decision-making actions and strategic development in the approx. 19,200 km² territory. This LSM was developed by applying a generalized additive model (GAM) over a set of meaningful explanatory variables (Bell et al., 2013; Petschko et al. 2014). Predictions were performed individually on the basis of sixteen lithological units. The final map was classified into three susceptibility classes ("low", "medium", and "high") to provide an easily interpretable map to decision-makers. By design, the "low" landslide susceptibility covers 78% of the territory and contains 5% of the landslides. The "medium" susceptibility class covers 16% of the territory while containing 25% of the landslides. The "high" susceptibility class covers 6% of the territory, containing 70% of the landslides (Bell et al., 2013; Petschko et al. 2014).

Since the maps have been calculated, however, many new landslides have occurred and despite the good acceptance by the stakeholders, questions about the actual accuracy of this original susceptibility map arise. The open question of the need for updating these landslide susceptibility maps is on the table. Therefore, a new research study has started to evaluate the performance of the existing maps and suggest a framework to update the LSM after new landslide occurrences. Recently mapped landslides (not used in the construction of the past maps) were obtained from two different sources: a) BGK (a building ground registry): damage reports related landslides (491 observations); and b) IMASS (a study mapped all landslides as polygons): landslides mapped from hillshade of a high-resolution LiDAR DTM (2006 observations). An identical methodological design is applied to both datasets in order to allow a comparison between the resulting maps. Consequent changes in spatial prediction are quantified and explored.

Preliminary analysis suggests that the adequacy of the former map to predict the unknown landslides is adequate but highly determined by the inventory characteristics (i.e., inventory quality and mapping method). For instance, ~61% of the IMASS landslides were correctly predicted to occur over the highest susceptible zones of the old maps. For the BGK landslides, this percentage was observed to be rather lower (~36%). Additionally, it was observed that most of the new landslides occurring in other less susceptible classes (i.e., "low" and "medium") were located close to the highest susceptibility class. For instance, more than 80% of either BGK or IMASS observations are 40m or closer away from a predicted highly unstable zone of the previous maps. When it comes to updating the former landslide susceptibility with the recent landslides, partial results suggest for the regional scale that most of the territory (88%), remains with the same predicted landslide susceptibility class as it was previously. However, the arrangement inside the individual lithological units might differ. For instance, for the Flysch zone, where most of the new landslides were mapped (1119 new observations), the landslide susceptibility is in 90% of the pixels, classified as the same as before. Strategies and methodologies for comparing old and new LSM will be discussed while an updated version of the LSM will be presented.

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P4.18
UPSCALING AND DOWNSCALING LANDSLIDE SUSCEPTIBILITY MAPS

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Although without official standardization, landslide susceptibility models (LSM) have entered preliminary stages of design and planning practice worldwide. As design and planning itself undergoes from lower to higher level of detail, different scales of LSM apply. Nevertheless, the LSMs are mainly produced in regional scales, whereas national and local are rarely available.

Limitations of downscaling and upscaling LSMs are considered herein, by comparing LSMs coming from continental scale on one hand, and regional scale on the other, while the validation was performed using national scale model (Figure 1) at 30 m pixel resolution. Pan-European model (Wilde et al. 2018) is downscaled from 200 to 30 m pixel resolution using re-gridding method based on various interpolation techniques (linear, spline, Kriging) over the area of the City of Doboj in Republic of Srpska (Bosnia and Herzegovina). The LSM for the City of Doboj (Sandić et al. 2023) was upscaled from 5 to 30 m resolution using various resampling techniques (nearest neighbor, bilinear interpolation and cubic convolution). All maps were made using heuristic or combined heuristic approaches with standard landslide conditioning factors as raster inputs (geological, geomorphological, environmental, etc.).

The best performing downscaling option was spline interpolation, while cubic convolution gave the best match against the referent LSM for the upscaling. Other downscaling variants tend to pixelate the map at 30 m resolution, whereas upscaling was not that considerably affected by technique choice. For large scale urban planning and preliminary design it is important to avoid pixilation as much as possible and smoothen the susceptibility classes so they can be compared against various elements, such as road and railway network features (higher-order curves, bridges, tunnels) and urban fabric footprints (housing, industrial, infrastructure). Results indicate that downscaling can be misleading and should be avoided if there is time and resource to perform appropriate local or regional scale LSM.

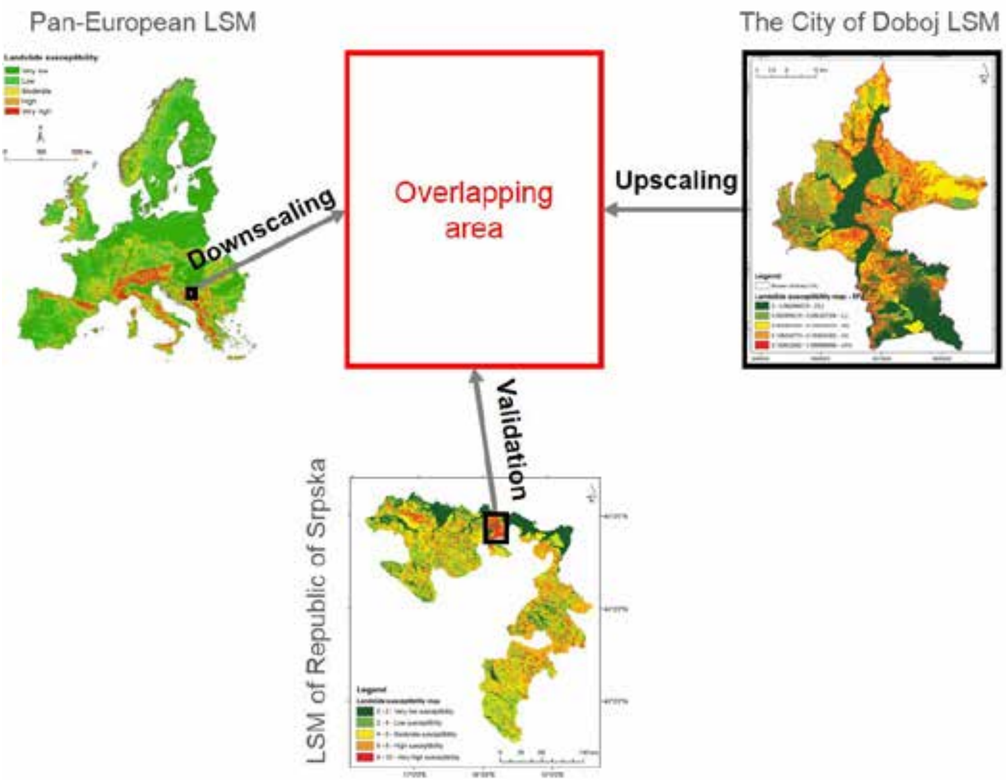

Fig. 1: Schematic of the Landslide Susceptibility Model comparison principle

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P4.19

EXPLORING FUNCTIONAL REGRESSION FOR DYNAMIC MODELING OF SHALLOW LANDSLIDES IN SOUTH TYROL, ITALY

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Shallow landslides are ubiquitous hazards in mountainous regions worldwide that arise from an interplay of static predisposing factors and dynamic preparatory and triggering conditions. Modeling shallow landslides at regional scales has leveraged data-driven approaches to separately investigate purely spatial landslide susceptibility and temporally varying conditions. Yet, the joint assessment of shallow landslides in space and time using data-driven methods remains challenging. Furthermore, dynamic factors have been typically included in data-driven landslide models as scalar predictors by employing aggregated descriptors over time (e.g., mean, maximum, or total precipitation over a defined time window), where many choices are possible for the considered time scales and aggregation operators. Therefore, incorporating the time-varying behavior of dynamic factors remains difficult.

This study addresses these challenges by exploring Functional Generalized Additive Models (FGAMs) to predict the occurrence of shallow landslides in space and time within the Italian province of South Tyrol (7,400 km^2). In contrast to conventional techniques, we test the benefits of using functional predictors to describe dynamic factors (e.g., precipitation and temperature) leading to landslide events. In other words, we evaluate dynamic factors as collections of measurements over time (i.e., time series). To do so, our approach uses a binomial FGAM to analyze the statistical associations between the static factors (scalar predictors), the dynamic weather conditions prior to a potential landslide occurrence (functional predictors), and the occurrence of shallow landslides in space and time.

Potential outcomes of this novel approach show an overview of the added value of using functional predictors for space and time shallow landslide modeling. These research findings are positioned within the context of the PROSLIDE project, which has received financial support from the Research Südtirol/Alto Adige 2019 research program of the Autonomous Province of Bozen/Bolzano – Südtirol/Alto Adige.

P4.20
DEEP LEARNING-BASED LANDSLIDE MAPPING USING MULTI-SENSOR SATELLITE IMAGERY

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Motivation: Intensification and increased frequency of extreme weather events due to the changing climate coupled with population urbanization is believed to increase the landslide hazard worldwide. Landslides often occur unpredicted and may result into loss of human life and property. Timely delivered information on the landslide location and extent as well as on the type and grade of damage is crucial to enable fast crisis response, i.e., to support rescue and humanitarian relief operations.

Methods: This study aims to examine the applicability of a convolutional neural network (CNN) based on the U-Net architecture for mapping landslides using freely available optical and synthetic aperture radar (SAR) data from the Sentinel-2/1 satellites. Following research questions are investigated: (1) How accurately can we map landslides using 10m spatial resolution remote sensing data? (2) Does the addition of more pre- or/and post-event SAR scenes help to increase classification accuracies? (3) Does the combination of optical and SAR features result in better accuracies compared to single sensor features? The investigation is done within the framework of Multisat4slows project (Multi-Satellite imaging for Space-based Landslide Occurrence and Warning Service), financed by the Helmholtz Imaging 2020 call.

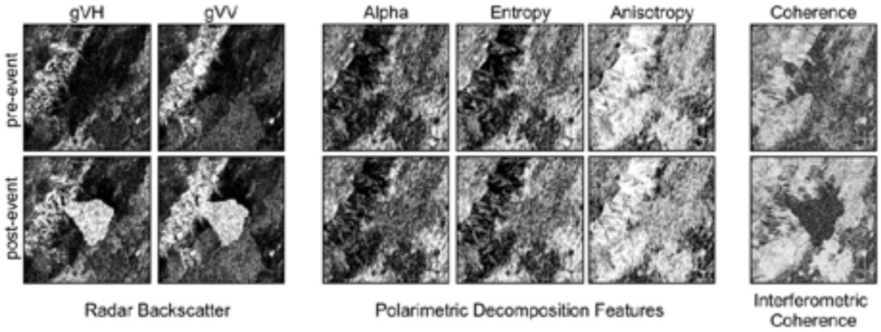

Fig. 1: SAR features of a large landslide in Hitardalur valley, Iceland, in 2018.

To address these research questions, we adopted the state-of-the-art semantic segmentation model – U-Net to map landslides based on limited and globally distributed landslide inventory data that we manually gathered from various sources. In total, 433 image patches with 128x128 pixels size were randomly split into 80% for training/validation of the model and 20% for testing it. To increase the number of training patches, we applied geometric image augmentation methods such as four-directional rotation, vertical and horizontal flipping. Four visible, one near-infrared, four red-edge and two short-wave infrared bands from Sentinel-2 A/B pre- and post-event scenes were considered in the study along with the Normalized Difference Vegetation Index (NDVI) calculated for each optical scene. Sentinel-1 data was used to acquire co- (VV) and cross-polarized (VH) radar backscatter values in gamma naught. Furthermore, we calculated polarimetric decomposition features (Alpha angle, Entropy and Anisotropy) and the interferometric coherence (Figure 1). SAR features were calculated for three pre-event scenes and three post-event scenes. Copernicus Digital Elevation Model (DEM) data are used to integrate land surface elevation and slope information into the classification process.Preliminary results and outlook: The preliminary results on validation data showed promising landslide mapping accuracies when SAR backscatter and interferometric coherence (one pre- and two post-event) are combined with NDVI (Dice - 0.929, Intersection over Union - 0.902). The accuracies on one, two or three pre-event scenes did not substantially differ, indicating no added values of increasing pre-event SAR features.

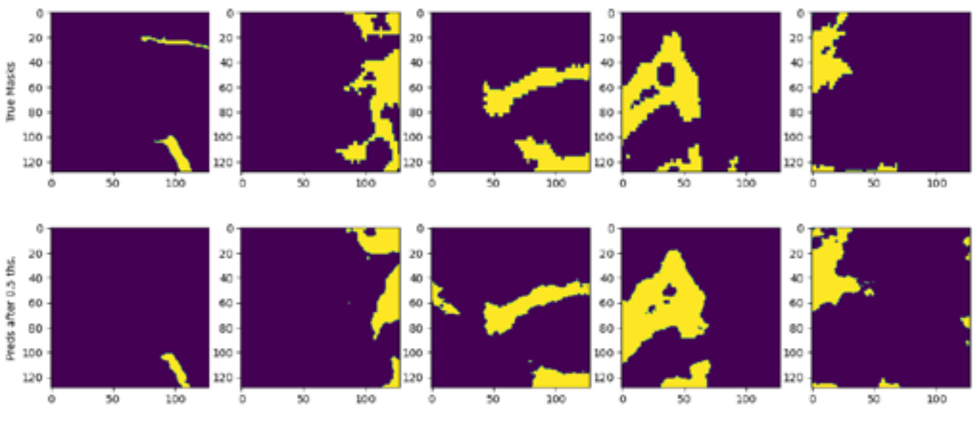

Fig. 2: Image patches (128x128) of masks with true (first row) and predicted labels (second row).

The workflow is planned to be tested on spatially and temporally independent test sets to examine how well U-Net models can generalize and predict new landslide events that were not used for training the model.

P4.21

ROLE OF BASELINE LANDSLIDE INVENTORY ON THE SENSITIVITY OF SUSCEPTIBILITY MODELS

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Purpose: Multivariate logistic regression models are the most popular in estimating landslide susceptibility by assessing various landslide causes—covariates—in mapped landslides. Although the sensitivity of these models to the variety of input data is frequently tested, the influence of data quality on the model accuracy is rarely discussed. Additionally, the properties of the mapped landslides, such as sample size, location, type, or time, are crucial to set a robust susceptibility model. Using an inventory that predominantly covers larger landslides would hinder a model by broadly covering the diversity of the factors leading to slope instability. Whereas smaller landslides could fail to capture sufficiently the range of values in the covariate space, likely decreasing the model performance. Another aspect is whether the number of mapped landslides is enough to estimate the susceptibility accurately or does more data means a better model.

Methods: We developed several simple logistic regression models to answer all the above-listed questions relevant to assessing the model sensitivity.

Results: We found that using only part of the individual landslides surprisingly may suffice to make accurate susceptibility estimates. Using smaller landslides in a susceptibility model outperforms a model that relies on larger landslides. Lastly, the model performance marginally varied after progressively adding more landslide data in a pilot study.

Conclusions: This study demonstrated that all existing landslide susceptibility models that rely on single landslide dataset might be overestimating their own diagnostic performance by about 5 percent. Yet, including temporal sampling in developing a model and tailoring the susceptibility model towards certain landslide failure types, such as slides or debris flow, might improve model performance.

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P4.22

INFLUENCE OF GEO-ENVIRONMENTAL FACTORS ON SHALLOW LANDSLIDE SUSCEPTIBILITY IN DIFFERENT ENVIRONMENTS

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Purpose: Shallow landslides are widespread and potentially dangerous phenomena whose triggering can be related to different environmental and climatic settings, making the understanding of their genesis difficult to achieve. The aim of this work is to evaluate the importance of different causative landslide factors by means of statistical techniques in study areas characterized by different geological, geomorphological, and climatic features, and to test if these analyses can reveal possible important processes connected with slope instability.

Methods: For this purpose, two different basins were chosen, the first (220 km2) on the western side of Lake Como and the second (Orba catchment, 808 km2) located between Piedmont and Liguria. Among the different available statistical techniques, we selected the logistic regression due to its widespread application and the facility to analyse the importance of each conditioning variable. The chosen explanatory variables comprise traditional geomorphological parameters, lithologic, pedologic and land use descriptors, and meteorological factors, with a partitioning of the study areas in slope units. The model results, obtained after the division of the original dataset into a training and a validation group, were evaluated through the values of the area under the receiver operating characteristic curve, AUROC. Moreover, several statistical models given by different combination of the describing factor groups were run in a bootstrapping procedure, allowing the identification of the most influencing variables.

Results: The AUROC values obtained from the models ranged between 0.52 and 0.73 for the first site, and between 0.68 and 0.91 for the second site. In both cases, the highest result was given by the combination of all the explanatory variables groups, while the lowest was obtained by using the land use factor only. Considering all the covariates, geology and land use are the most influencing ones, more than geomorphological parameters. Among the meteorological factors, both the total cumulated rainfall and the maximum rainfall intensity characterizing the event are chosen, although their coefficient values are never of high impact. Interestingly, slope gradient seems not to be one of the factors most affecting the models. While running the models with only one explanatory group, the best result was obtained by using meteorological factors, for the first area, and by using lithological factors, shortly followed by the geomorphological ones, for the second area. This may suggest that instabilities in the first area are directly controlled by the rainfall amount, while in the second area the landslide initiation seems to be controlled by more complex hydrogeological processes.

Conclusions: Our findings suggest that the analysis of the influence of different types of causative factors can help in the understanding of the controlling processes of shallow landslides in different geo-environmental settings, thus helping in the definition of more targeted investigations.

P4.23

HOW TO GAIN KNOWLEDGE ABOUT UNCONSOLIDATED HILLSLOPE MATERIAL FOR REGIONAL LANDSLIDE SUSCEPTIBILITY STUDIES?

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State of Research and Current Challenges: Knowledge about areal distribution, thickness and geophysical properties of unconsolidated hillslope material or regolith (including sediments, weathering products and soils) above fresh bedrock is crucial to evaluate sliding and flowing landslide failure modes. However, in many landslide susceptibility studies input of geological underground information is either absent or limited (compare Reichenbach et al, 2018). When it is used, it is often based on geological bedrock maps, which offer no or only limited information about regolith. This circumstance is known and has been outlined by many authors. Several methods to improve the estimation of spatial extent and geophysical properties of unconsolidated hillslope material have been studied and suggested over the last decades and years, including geological mapping, geotechnical underground investigations, accompanied by laboratory testing, and terrestrial geophysical methods. Once studies cover large areas (several km2) applying some of these methods is labor-, time- and cost-intensive and consequently their use often becomes infeasible. Other approaches towards solving this challenge include landscape evolution and soil development computer models. However, such models are based on the use of digital elevation models, which are re-used in susceptibility models, posing the possibility of errors due to redundant data use.

Research Question and Methods: The question remains, if there are methods, which are comparatively time- and cost-efficient and result in knowledge about unconsolidated hillslope material in mountainous and partly vegetated terrain beyond what available official (bedrock) maps offer and in addition to what traditional methods provide? With this framework in mind, the focus in the presented research lies on supporting conventional field and laboratory methods with simple terrestrial remote sensing methods, such as the use of mobile phone cameras and hand-held LiDAR sensors to speed up the data acquisition and analysis process for regolith.

Results: It is anticipated that the results show possibilities to support the mapping and data acquisition process with easily collectable remote sensing data, which can be analyzed to arrive at additional information about grain size distribution, which allows for the estimation of geotechnical characteristics of unconsolidated material on top of bedrock. It will be a time-efficient way to obtain better estimates in regard to the geotechnical properties of unconsolidated material than what bedrock maps can provide. The methods, however, exclude vital information about areal extent and thickness of regolith. Perspective future studies therefore include testing the feasibility of using geophysical sensors mounted on drones to deliver better estimates in regard of regolith's thickness plus geotechnical properties over large and also inaccessible areas.

Conclusions: An optimized understanding of the regolith cover gained with simple terrestrial remote sensing methods will be a further step into introducing methods, which can be used for improving input data for landslide susceptibility studies over large areas with comparatively less cost and time than conventional field and laboratory methods.

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P4.24
DEFINITION OF RAINFALL THRESHOLDS FOR SHALLOW LANDSLIDES IN COLOMBIAN TROPICAL MOUNTAINOUS CATCHMENTS ACOPLING PHYSICALLY-BASED MODEL TRIGRS AND PROBABILITY DENSITY FUNCTION

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Purpose: Landslides generate economic losses and human fatalities worldwide, especially in mountainous and tropical countries like Colombia. According to the Geohazards database (www.geohazards.com.co), 10.438 landslides were registered in the Colombian Andean between 1921-2020, with almost 7.313 fatalities. The Colombian Andean region exhibits a complex tropical hydrometeorological dynamic affected by different temporal and spatial scale climate processes. It comprises a diverse geological and geomorphological setting characterized by steep slopes and morphogenic conditions predisposed to gravitational hillslope processes. Most of the Colombian population is established in the Andean region occupying large hilly areas without adequate planning control representing a risk condition that in recent years has encouraged the development of forecast models like Rainfall Thresholds and more complex and complementary tools like Early Warning Systems (EWS). Empirical-statistical and physically-based methods can define EWS based on rainfall thresholds. Empirical statistics are based on historical data on rainfall and mass movements. Physically-based models consider the effects of rainfall coupling distributed hydrological and geotechnical models providing landslide spatial distribution by calculating the distributed safety factor.

Methods: Physically-based rainfall thresholds consider the spatial distribution or location of the landslides by approaches grounded on physical laws that consider the occurrence of landslides by calculating statistical or distributed safety factors. They are based on the physical relationship between soil resistance forces and hydraulic-dynamic forces associated with rainfall instability effects, considering the impact of rainfall coupling hydrological and geotechnical models. This dynamic nature of subsurface hydrology depends on the complex interactions among precipitation inputs, physical properties, and heterogeneity of soils, bedrock, local geomorphology, vegetation, and associated biomass. These factors influence (i) the timing of landslides with respect to precipitation inputs and antecedent soil moisture, (ii) landslide type and failure mode, providing a comprehensive understanding of the physical behavior of the rainfall throw the hillslope and associated infiltration. These models provide the spatial and timing distribution of the phenomenon.

Results: The definition of the rainfall thresholds integrates IDF gauge-based rainfall data and the physically-based model (TRIGRS) to calculate the cumulative density function from the histogram of the distributed safety factor within a basin, providing a better comprehension of the response to heavy rainfall events in a catchment scale in tropical mountainous terrains (Figure 1) where actual climate change affects impulses the develop of novels tools that can complement Early Warning Systems (EWS).

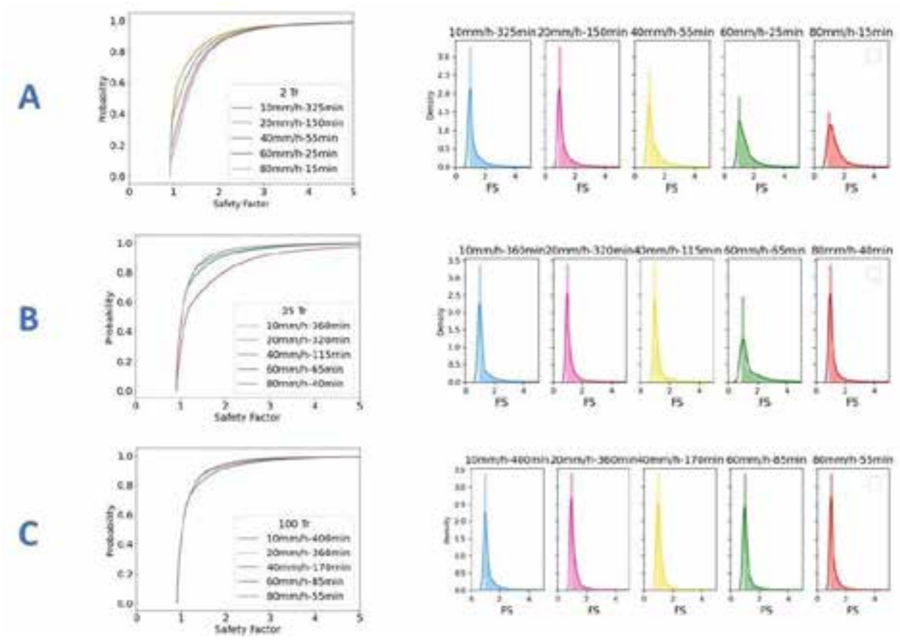

Fig. 1: Cumulative Density Function CDF Curves and Histograms of the distributed Safety Factor in Basin A for two years of return (Tr2) (A), 25 years of return (Tr25), and 100 years of return (C).

Conclusions: The goal of this methodology is to perform a statistical analysis by calculating the area under the probability density function (PDF) from the resulting histogram of the calculated distributed safety factor by TRIGRS in the catchments, allowing to pursue a unique/natural threshold or limit condition for shallow-landslides in each catchment according to the correlation between the morphometric parameters of the assessed catchments and the resulted area under the probability density function.

P4.25
CALIBRATION AND VALIDATION OF PHYSICALLY BASED DISTRIBUTED MODELS FOR SHALLOW LANDSLIDES PREDICTION

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Purpose: Rainfall-induced shallow landslides are phenomena which can rapidly evolve into debris flows characterized by high velocity and destructive power. In this study, in order to prevent them or at least predict them over a large area, two physically based distributed models were calibrated, validated and compared, HIRESSS (Rossi et al., 2013) and Scoops3D (Reid et al., 2015).

Methods: HIRESSS is a numerical model for slope stability, providing distributed factor of safety (FS) maps in response to rainfall events and it's based on infinite slope model. HIRESSS was applied to the entire Alert Area A, one of the 4 alert areas into which the Valle d'Aosta region is divided for civil-protection purposes, the central area of the region, selecting two rainfall events, occurred in 2013 and 2020, which triggered shallow landslide phenomena in such area. Scoops3D is a limit equilibrium model using analysis methods that assume a circular geometry of the rupture surface. ScoopsD was applied to 4 municipal sub-basins defined within the selected warning area, characterized by reports regarding the same rainfall events. Due to internal problems with the Scoops3D software, only two opposite scenarios of fully saturated soil and fully dry soil were assumed. The geotechnical and hydrological input parameters required for the applications of the models were obtained from laboratory tests and on-site investigations. In the indicated sub-basins and for the set saturation conditions, a comparison was made between the outputs generated by the models in terms of distributed raster maps of factors of safety (FS) with a 10-m resolution.

Results: The HIRESSS model detected unstable areas in all the sub-basins analyzed, while Scoops3D did not detect in any case and for any saturation situation considered, unstable pixels interesting the surface covers. One of the main causes of the different results observed in the output provided by the models is represented by the geological and geomorphological regional context, which is characterized by a shallow thickness of the soil covers and a high energy of the relief, a context in which the landslides are often marked out by low depth-to-length ratios of the sliding surfaces. Thus, the infinite slope approach used by HIRESSS appears to be the most suitable model to describe the triggering of landslide phenomena in the sampled area.

Conclusions: The results represent a first step in the definition and understanding of the triggering mechanisms of landslide phenomena that affect the Valle d'Aosta region during severe rainfall events, as well as an important tool to support the competent authorities in land-use planning and in the assessment of anthropized areas at high risk.

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P4.26

DATA-DRIVEN SUSCEPTIBILITY ASSESSMENT INTEGRATING PREDISPOSING FACTORS DERIVED FROM ENGINEERING GEOLOGICAL MAPPING

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Purpose: In the field of landslide susceptibility assessment by means of data-driven methods, geology is among the most widely used predisposing factors. Geological information like lithology, chronostratigraphy, distance to tectonic lineaments or structural setting, are often used. Recently some authors compared the sensitivity of different geological information and pointed out that each of them can account for specific contribution for landslide predisposition assessment. Nevertheless, engineering geological properties are rarely used when data-driven models are implemented since they require time consuming and costly procedures for their acquisition. In recent years, we developed and applied a new semi-quantitative and repeatable procedure to characterize sub-surface geological units integrating the geological map, as the basic information, with a large dataset of outcrop scale lithological, stratigraphic, structural, and engineering geological observations. In this work we analyse the relevance of these new map scale data in respect to the landslide distribution and data-driven susceptibility assessment.

Methods: The procedure implemented for the near-surface engineering geological mapping of geological units involves the extensive use of the Schmidt's hammer at the outcrop scale integrated with laboratory tests, such as the Slake Durability Test and the determination of rock unit weight. The results allow us to obtain the quantitative classification of a wide set of geological formations following four classifiers (one lithological, three engineering geological) and corresponding cartographic representation.

Landslide susceptibility representations based on the Logistic Regression algorithm were obtained by integrating different combinations of these classifiers and other morphometric predisposing factors for the Alpi Apuane region (northern Tuscany, Italy).

Results: Preliminary results show a correlation between landslide distribution and engineering geological classifiers. These classifiers also allow to highlight that single geological formations may be split into two or more regions characterized by different engineering geological properties. This suggests that an automated lithological classification of formations may fail on accurately conditioning landslide susceptibility. Finally, the highest the prediction rate accuracies were obtained for those scenarios where engineering geological classifiers were added as predisposing factors.

Conclusions: In conclusion, despite the fact that near-surface engineering geological mapping implies spending further efforts in terms of resources and time, this information allows to strengthen the predictive capability of data-driven landslide susceptibility methods.

P4.27
RELEASE AREAS FOR SHALLOW LANDSLIDES ON OPEN SLOPE IN NORWEGIAN LANDSCAPE: METHOD DEVELOPMENT FOR LANDSLIDE RISK ASSESSMENT

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Purpose: Norway's geological, geomorphological, and climatic conditions make the country susceptible to shallow landslides. To improve hazard assessment, prevention, and management, there has been an increasing interest in studying these processes in Norway. The Geological Survey of Norway (NGU) in close collaboration with the Norwegian Water Resources and Energy Directorate (NVE), has been working to identify the local conditions that contribute to shallow landslide occurrences, such as topography, hydrology, vegetation, and sediment characteristics. A better understanding of these conditions will improve hazard assessment, inform decision-making, and, consequently, enhance the quality of the recommendations and guidelines for risk assessment.

Methods: This study utilized starting points of open slope shallow landslides, mapped on detailed quaternary maps (1:10’000) produced by NGU through fieldwork investigation, remote sensing analysis, and landslide inventories. Statistical analysis of the landslide inventories was conducted in order to determine the main distribution of the following: types of sediments, lithologies, slope range, curvature of the terrain, catchment areas, vegetation, and other parameters. A selection of locally representative sites was identified on the basis of their mapped morphology, slope, and type of sediment, and thereafter was visited to describe the observed geological setting, sediments, and structures (backscarp, lateral limits, distance to bedrock, slope of the sliding plane). Samples were taken for analysis of grainsizes and mineral composition.

Results: For the preliminary results, we performed statistical analysis on 448 starting points and backscarp lines for shallow landslides from the landslide inventory. They occur on slopes ranging from 17 to 44 degrees, though the majority have a slope between 25 and 30 degrees. They are found on diverse types of materials, although most of them occur in moraine sediments (thin and thick layer). We observed that a greater contrast between fine and coarse sediment layers causes water to increase pore pressure at their intersection. Furthermore, where a layer of diamicton with a high content of fine material forms an impermeable layer at the bottom of the profile, mass movement is facilitated. Finally, landslides on shallower gradients seem to be related to areas with human agriculture and/or little vegetation.

Conclusions: Susceptibility maps are an essential part of understanding landslides, but further research is needed to understand the triggers and mechanisms of landslide occurrence. This is vital to improve safe areal planning, as well as communication and collaboration between researchers, management, and local communities for better landslide assessments and prevention. This study aims to improve guidelines used by consultants in Norway for mapping risk areas.

P4.28

THE USE OF ROCKFALL DATA IN STATISTICAL ANALYSIS AND FOR THE VALIDATION OF ROCKFALL HAZARD ZONING

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The collection of rockfall data is adjusted according to the research objectives and project framework, such as financial and temporal constraints and the size and settings of the study area.

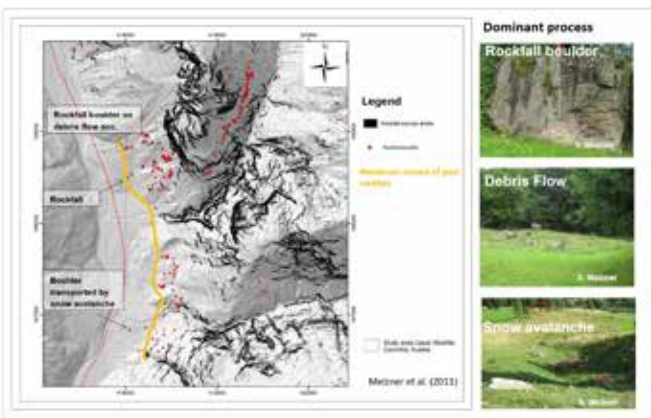

Figure 1: The reliability of rockfall boulders mapping for rockfall hazard zoning depends highly on the experience and the cautions of the investigator.

The characteristics and quality of the resulting rockfall catalogues (figures 1 and 2) depend on (i) the setting and characteristics of the study area (e.g., topography, geology, land use, forest cover), (ii) the accuracy of the base and thematic maps, (iii) the methods and techniques used, (iv) the source(s) of information, (v) the experience of the investigators, (vi) the time available for the investigation, and (vii) the available human, technological and economic resources. Depending on the scale of investigation the individual rockfall features – e.g., release area, impact points, talus slopes and single deposited boulders – are represented by points, lines or polygons (Melzner and Guzzetti, 2004; Melzner et al., 2020). Historical rockfall records usually lack of a complete information on both the timing of the event and the size of the rock, which are usually referred in relative terms (i.e., "very often", "large", "destructive/catastrophic event"), or are estimated in the field in pre-defined size classes (Figure 2). Rockfall descriptions in historical accounts may contain sufficient detail to determine the exact rockfall locations, including release and deposit area. However, in other historical reports the location is only mentioned vaguely referring to segments of valleys/roads/trails/villages or regional toponyms. Often the informal (local) place names reported in the historical reports are not mentioned/published in official (topographic) maps. From a statistical perspective, rockfall datasets are nearly always incomplete. Although simple heuristic and statistical frequency-based methods can be used for the basic rockfall catalogue analysis and characterization, additional non-parametric methods have to be developed to cope with scarce data entries, to close data gaps, and to support the identification of shared standard methods for rock fall time series and rockfall size analysis.

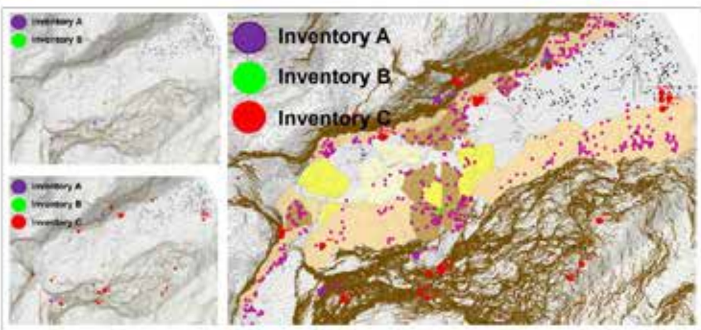

Figure 2: Representativeness of rockfall data. Comparison of three catalogues of historical rockfall events (inventories A-C) with a catalogue of rockfall size (pink points), talus slopes (light brown polygons), large rockfall accumulations (brown polygons) and fluviatile and glacial accumulations (yellow accumulations) (Melzner and Guzzetti, 2014).

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P4.29

IMPORTANCE OF DISCONTINUITY TRACE MAPPING IN ROCKFALL SUSCEPTIBILITY ASSESSMENTS USING HIGH-RESOLUTION 3D POINT CLOUD ANALYSIS

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Purpose: The kinematic analysis based on a simple Markland test (Markland, 1972) is one of the quickest methods for assessing rock mass stability for different types of failure. Since the method is based on discontinuity orientation data, it is essential to investigate the influence of mapping techniques (manual and semi-automatic) on discontinuity network characterization and, therefore, on the results of kinematic analysis. For the analysis purpose, a MATLAB code was developed to assess rockfall susceptibility using the Kinematic Hazard Index (KHI) (Casagli & Pini, 1993).

Methods: For the case study, a rock slope composed of Upper Triasic dolomites in Gorski kotar region in Croatia was chosen. Terrestrial laser scanning (TLS) was used to generate a 3D Point Cloud. Discontinuities were mapped manually using open-source software Cloud Compare V2.12 and semi-automated using Discontinuity Set Extractor (DSE) v3.0 (Riquelme et al. 2014). Results were validated with fieldwork data to determine which methodology correctly represents a discontinuity network. Rockfall susceptibility assessments were done using in-house MATLAB code, by calculating values of the Kinematic Hazard Index for each point of 3D Point Cloud.

Results: Structural analysis performed by manually mapping discontinuities resulted with approximately 500 discontinuities, subdivided into five sets, bedding plane and four joint sets. The most dominant discontinuity set is the bedding dipping out of the rock face, visible predominantly as a trace on a rock face. On the other hand, semi-automated mapping using DSE recognised more than 1900 discontinuities, subdivided into five discontinuity (joint) sets, with significant dissipation of discontinuity orientation data. The most dominant discontinuity sets are predominantly sub-vertical with variable dip angle, while the bedding was not recognised due to its visibility as s trace. Based on the acquired input data, a 3D rockfall susceptibility assessment was done to determine the influence of the mapping technique on susceptibility to planar failure. Preliminary susceptibility analysis based on manual mapping resulted in KHI values ranging from 0-28% with a mean value of 12%. On the other hand, susceptibility analysis based on semi-automated mapping resulted in KHI values ranging from 0-30% with a mean value of 5%.

Conclusions: The analyses imply that in the case of complex discontinuity network conditions, results of discontinuity mapping using semi-automated methods should be verified. The advantages of both manual and semi-automated mapping have to be utilised in order to obtain a correct representation of the discontinuity network settings. If structural analysis results are not verified by manual mapping, discontinuities with unfavourable orientation may be neglected, leading to incorrect conclusions regarding rockfall susceptibility.

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P4.30
INVESTIGATION OF THE ROCKFALL TRIGGERING MECHANISMS IN SLOVENIA, EUROPE

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Purpose: Rockfalls are one of the natural hazards that can endanger infrastructure and cause large economic damage and in some extreme situations also endanger human lives. Rockfalls are the result of a long geologic process (tectonics, weathering, etc.), but the fall is sudden. The question is what causes rockfall (what factors) and how this happens (what mechanisms)?

Methods: Hence, in order to investigate rockfall triggering factors, we have collected a database of more than 2,500 rockfalls (Slovenian Infrastructure Agency) identified in year 2021 on or near the road network in Slovenia, Europe. The database contains the information about the date, road network ID, short description of the conditions and whether the rocks on the road were smaller or larger than 20 cm. The database was linked to GIS layer of road network in Slovenia. Basic temporal and spatial analyses were conducted and a preliminary analysis of the triggering conditions was carried out.

Results: The preliminary results indicate that most of the rockfalls were triggered in colder part of the year from January to April. Much smaller number of occurrences were detected in summer. In terms of spatial analysis, much larger number of rockfalls occurred in western part of the country compared to eastern part of the country. This can be explained by the higher erosive power of raindrops (one of the triggering mechanisms) and higher terrain slopes in western part of the country. Quite interestingly, relatively low number of rockfalls was detected in the Mediterranean part of the country where wind speed can be relatively extreme, which could be another triggering mechanism. Additionally, for the selected catchments (i.e., Soča and Idrijca Rivers) we have investigated relationship between the meteorological data and the rockfalls occurrences. For these areas, the highest correlation was obtained between the maximum wind speed and the number of rockfall occurrences. However, no clear triggering mechanisms could be identified based on the so far conducted analysis. It seems that lithological and geomechanical characteristics of rocks and slope of the terrain are mostly determining the locations of rockfalls in Slovenia (Figure 1).

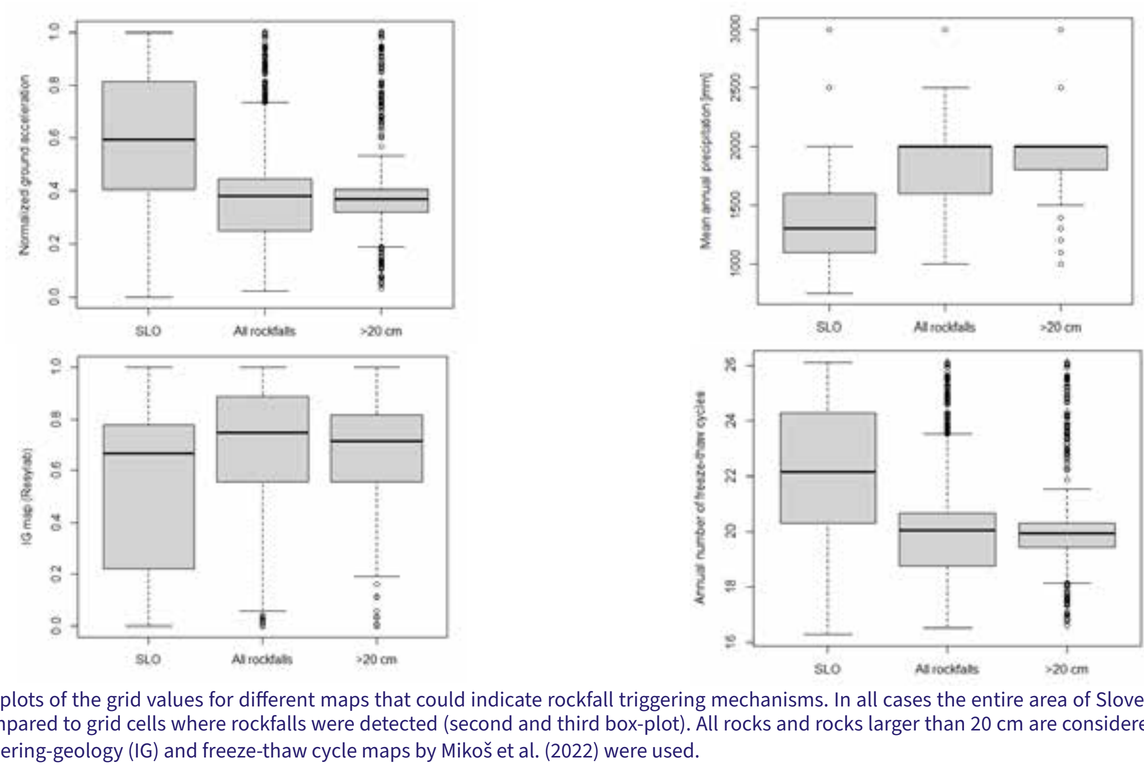

Fig. 1: Box-plots of the grid values for different maps that could indicate rockfall triggering mechanisms. In all cases the entire area of Slovenia (first box-plot) is compared to grid cells where rockfalls were detected (second and third box-plot). All rocks and rocks larger than 20 cm are considered separately. The engineering-geology (IG) and freeze-thaw cycle maps by Mikoš et al. (2022) were used.

Conclusions: This paper shows the preliminary analysis conducted in relation to the rockfall triggering conditions in Slovenia. Further research will be performed to better quantify rockfall triggering mechanisms.

Acknowledgments: The results of this study are part of the ongoing research projects funded by the Slovenian Research Agency (J1-2477 and J1-3024) and the IPL project No. 262.

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P4.31

SOURCE AREA DEFINITION AND ROCKFALL MODELLING IN EL HIERRO (CANARY ISLANDS, SPAIN)

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Purpose: The Canary Islands are characterized by steep topography and geological complexity that significantly influence hillslope dynamics and failures occurrence. Rockfalls are common in this region, posing a significant threat to society, with the potential for loss of life, infrastructure disruption, and destruction of livelihoods. Accurate rockfall modeling is crucial to assess rockfall hazard and risk and requires the analysis of various factors, including parameters controlling the boulders detachment and their trajectories. Erroneous definition of source areas can result in unrealistic representations of the rockfall process, as well as inaccurate parametrization of runout software simulation may lead to sensible differences in rockfall hazard estimation. In this study, specifically, we analyse how different approaches used to define source areas can affect the rockfall modelling.

Methods: To assess rockfall source areas, we initially adopted a morphometric approach based on slope thresholding. The slope angle threshold was determined through the combination of geomorphological information, geological analysis, and past rockfall event analysis. Additionally, to identify source areas, we proposed a probabilistic approach, implementing statistical models that use the observed source areas as dependent variable and a set of thematic information as independent variables (e.g., morphometric parameters derived from DTM and lithological information). For this purpose, we selected different training and validation samples to identify possible biases or errors. Rockfall runout modelling was performed with STONE, a physically based 3D software, using in input source areas identified with the different approaches (i.e., probabilistic and slope threshold).

Results: The island of El Hierro (Canary Islands, Spain) was selected as test area due to its geomorphological and geological context. We used the 5m x 5m Digital Elevation Model provided by the National Geographic Institute, and the parameters (i.e., friction and restitution coefficients) determined on similar analyses performed in other islands of the Canarian archipelago. The main outcome of the rockfall modeling was the map of the rockfall trajectory counts, which portrays the territory potentially affected by rockfall processes. Different approaches were used to prepare the susceptibility maps based on unsupervised and supervised classifications.

Conclusions: Rockfall source areas obtained using different approaches affect largely rockfall runout modelling zonation. Such analysis provides directions on the appropriate modeling of rockfall to support civil protection, emergency authorities and decision makers in the evaluation and assessment of the potential rockfall impacts and can be a strategic support for rockfall warning systems.

P4.32
USING MULTI-TEMPORAL DIGITAL TWINS OF NAVAGIO BEACH (ZAKYNTHOS ISLAND, GREECE) FOR THE DETECTION OF ROCK DISPLACEMENTS AFTER THE 8.9.2022 EARTHQUAKE

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Unmanned Aerial Systems (UAS) have undeniably been acknowledged as one of the most efficient methods considering long-term landslide and rockfall monitoring. The 3D photogrammetric processing of aerial images, generated by using Structure-from-Motion (SfM) and Multi-Stereo (MS) techniques, is an advanced method for measuring rockfall volumes due to its capability to provide high vertical and horizontal resolution (Peppa et al., 2019). As an alternative to Terrestrial or Airbourne Light Detection and Ranging (LiDAR), UASs are considered as a low-cost and flexible surveying tool, optimal to use in hazardous and inaccessible terrain. The purpose of this study is the detection of possibly loosened rocks, that could lead to potential rockfalls in the Navagio (Shipwreck) Beach of Zakynthos Island, in Greece due to an earthquake of 5.4Ml (8.09.2022). The first -out of two- flight survey was carried out before the earthquake and more specifically on July 20th, 2020, using a commercial multi-rotary UAS, which carries a Global Navigation Satellite System (GNSS) antenna, taking advantage of its ability for Real Time Kinematics (RTK) processing. The same equipment was used also at the post-earthquake survey, which was carried out on September 9th, 2022, just one day after the seismic event (Figure 1).

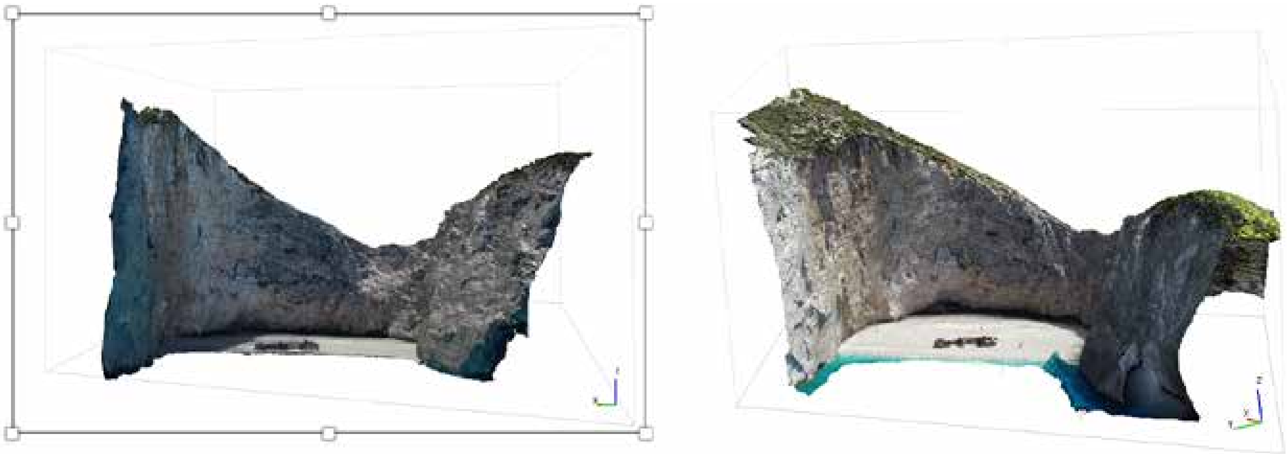

Fig. 1: Diachronic digital twins of Navagio Beach of 2020 (left) and 2022 (right).

The earliest survey was planned during a research project, whereas the latest survey was intentionally scheduled for acquiring comparable data, in terms of micro-topographical change detection across the steep slopes of Navagio beach. We chose the Network RTK approach for the first survey as this is a quite accurate and less time-consuming data acquisition technique (Panagiotopoulou et al., 2021). During this technique we managed to succeed the high precision Direct Georeferencing (DG), of the imagery captured by the UASs, which does not necessarily require GCPs. Moreover, we used the Post Processing Kinematics (PPK) approach, during the processing of the second survey image data, by including GNSS permanent station's RINEX data within the procedure, along with pseudo GCPs for better co-registration of the two datasets (Peppa et al., 2019). For the data analysis, we applied an Object-Based framework for failure zone mapping with the inclusion of spectral, spatial, and contextual characteristics (Karantanellis et al., 2020). Morphometric and spectral information and 3D change detection techniques have been translated in hazard parameters to delineate failure zones for landslide and rockfall assessment.

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P4.33

TECHNICAL-ECONOMIC FEASIBILITY STUDY FOR THE REDUCTION OF ROCKFALL RISK IN THE LOCALITY OF ST. MAGDALENA, MUNICIPALITY OF BOLZANO (AUTONOMOUS PROVINCE OF BOLZANO - SOUTH TYROL)

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Purpose: The Autonomous Province of Bolzano (APB) has already introduced hazard maps at municipality level in 2007. Hazard maps count as a fundamental requisite to enable preventive spatial planning and development. Further, these maps are indispensable for the accurate planning of protective measures and civil defense activities. The hazard map of Bolzano was approved in 2017, whereby a large part of the locality of St. Magdalena was linked to a very high hazard (H4) due to rockfall. This prevailing hazardous situation was confirmed by a rockfall event in January 2021, at the Hotel Eberle. During the rockfall event parts of the hotel were buried under several thousand cubic meters of rock material while miraculously loss of life could be avoided. In conjunction with the hazard map this event was taken as an occasion by the APB to conduct a detailed analysis of the slope area of St. Magdalena. Finally, these investigations paved the way for establishing a technical-economic feasibility analysis to reduce the hazard.

Methods: The following investigations were carried out:
- Consultation of previous investigations, studies and publications;
- Analysis of various aerial photographs, digital terrain models with different spatial resolutions and other GIS-based applications;
- Detailed geological-, geomechanical- and geomorphological mapping;
- Implementation and analysis of aerophotogrammetric and terrestrial laser scanning images;
- High-resolution, detailed photographic surveys of the rock areas;
- Statistical analysis of the mapped fall blocks and definition of the project block according to UNI 11211;
- Rockfall simulations with RAMMS::Rockfall;
- Evaluation of the existing rockfall protection structures in terms of dimensioning, positioning, and maintenance.

Results: During the field mapping, it became apparent that the area uniformly consists of ignimbrites of the Ora-Formation (Athesian Volcanic Group). These are locally characterized by a strongly varying degree of deconsolidation. This characteristic is expressed by areas bearing clearly pronounced fissures as well as by areas defined by massive and compact rocks. Data of >330 recorded fall and unstable blocks and results of the geological-geomechanical mapping were used to effect volume calculations and to conduct a statistical analysis. In view of the above-mentioned findings, it was necessary to define several project blocks depending on the extent of the unstable rockfall zones. Thus, these detailed analyses show that numerous passive and active rockfall protection measures are required to reduce rockfall risk in St. Magdalena; for instance, a double rockfall protection system must be provided due to the characteristic morphology, terrain slope and the lack of space due to urban planning.

Conclusions:
- A highly detailed hazard map provides an optimal basis for defining the prioritization of further planning and for ensuring the implementation of protective measures;
- The scenarios calculated in the hazard map with RockyFor3D are confirmed by RAMMS::Rockfall: this finding suggests that the respective software and the resulting scenarios are primarily driven by detailed results of the field mapping;
- A detailed technical-economic feasibility including a serious cost-benefit analysis counts as the pivotal point in minimizing problems that might arise in the subsequent planning and tendering phases.

P4.34

ACTIVE LANDSLIDE MAPPING IN URBAN MOUNTAINOUS SETTINGS THROUGH ADVANCED-DIFFERENTIAL INTERFEROMETRY SYNTHETIC-APERTURE RADAR TIME SERIES

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Purpose and Methods: Advanced-Differential Interferometry SAR (A-DInSAR) data represent an established tool to the management and monitoring of natural hazards, such as landslides, subsidence, earthquake displacements induced. This study is focused on the identification of areas affected by gravity processes related to landslide phenomena occurring in a wide sector of the Nebrodi mountain chain (northern Sicily). The considered procedure, implemented by Meisina et al., 2008 and Infante et al. (2019) using A-DInSAR data and the Model Builder tool (ArcGis), allows the semi-automatic mapping of sectors affected by significant displacement rates, so that clusters related to relevant displacements in large areas of the territory can be isolated. Satellite data used in the procedure are derived from multi-constellation imagery and cover a time interval ranging from 1992 to 2000 for ERS-1/2 data, from 2002 to 2010 for ENVISAT data, while COSMO-SkyMed (CSK) and SENTINEL-1 data cover the time intervals 2011-2014 and 2017-2020, respectively.

Results: The results show that most of the detected landslide movements affect urban centers, where the rates of displacement show both linear and nonlinear trends. Based on these outcomes, the kinematic model of the landslide phenomenon could be defined and the most affected urban centers, in terms of displacement rate and movement velocity, were identified. This allowed a quick recognition of the landslide activity in the analyzed sector, which is the basis of specific, focused analyses to be carried out at selected urban centers.

Conclusions: A semi-automatic procedure based on A-DinSAR analysis is proposed herein to map areas affected by active landslide phenomena in a morphologically and tectonically complex area such as the Nebrodi Mountains. The methodology used can be applied to numerous geomorphological contexts and allows the definition of useful information in landslides mapping and/or monitoring. The achieved map, combined with a time series analysis, provides a reliable indication of a landslides' trend and type, and it can be used for territorial management purposes. In fact, by recognizing the landslide activity in wide areas, a prioritization of prevention activities could be planned, in the frame of proper landslide risk management plans.

P4.35
DEBRIS FLOWS IN URBAN ENVIRONMENTS: COMBINING HAZARD AND EXPOSURE TOWARD A TAILORED EMERGENCY EVACUATION RESPONSE

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Purpose: Debris flows are one of the most dangerous types of landslides in mountain regions. Therefore, the urban development in these areas increase the exposure of population, structures and infrastructures, often leading to loss of lives and severe socio-economic impacts. In this work, we use a dynamic debris flow run-out model to simulate a worst-case scenario in a mountain region, several times affected by this type of landslide in the last two hundred years. Based on this scenario, different elements at risk are identified, as well as the exposed population per building and by age group, allowing to simulate different pedestrian travel times to safe areas.

Methods: The implemented methodology has the following sequence: 1) debris flow run-out modelling and estimation of flow velocities and thickness of the debris deposits; 2) identification of the buildings at risk; 3) estimation of the exposed population by using a dasymetric distribution; 4) calculation of the time between the debris flows initiation and the impact of the run-out in each one of the buildings at risk, which reflects the time required for evacuation; 5) calculation of the time needed for evacuees to arrive at safe meeting points while taking into account different travel speeds.

Results: We identified 96 buildings located in areas affected by debris flows deposits with thickness equal to or greater than 0.5 m, while around 4 % of these buildings are intercepted by a flow velocity above 3 m/s. Regarding the residents exposed to debris flows, 56 % are 65 years old or older. Moreover, we estimated that in 23 % of the buildings at risk, the evacuation time is longer than the arrival of debris flows, considering a slow walking speed (1.10 m/s).

Conclusions: The outputs of the dynamic model allowed the calculation of flow velocity, thickness of the deposits, volume and extend of travelled material, which constitutes critical parameters for hazard and risk assessment. The identified buildings at risk must be checked one by one and the resident's capacity to cope with an emergency evacuation (e.g. mobility difficulties, cognitive disorders...) needs to be assessed in order to define specific strategies. We advise to designate new safe meeting points or consider a vertical evacuation in circumstances where the evacuation time surpasses the arrival of the debris flows. If the latter is taken as an alternative, then the buildings' structural capacities must be evaluated.

Acknowledgements
This work is part of the project European ground motion risk assessment tool RASTOOL (DG ECHO).

P4.36

QUALITATIVE HAZARD ASSESSMENT AS FIRST STEP FOR LANDSLIDE CONSIDERATION IN URBAN PLANNING

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Purpose: ICGC handles the regulation of geological risk in Catalonia, which derives from the institution's own rules and the Urban Planning and Civil Protection law. In this sense, ICGC revises the geological risk studies that go with the legal procedures of territorial and urban planning figures. There is an intrinsic difficulty in the communication and understanding of the geological hazard and risks concepts and consequences by the people involved in planning. Also, in the sector there are different companies and professionals, who with different criteria prepare these geological risk studies, which means that the identification and assessment of the risk is mostly subjective and contributes to the difficulty of clearly communicating the risk. For this reason, ICGC decided to promote a set of methodological guides for carrying out geological risk studies that manage both the carrying out of these studies and the communication of action recommendations. The first of these guides is focused on setting up common criteria for the identification of potential risks and the qualitative hazard assessment.

Methods: The guide plays a key role in the global strategy for the geological risk prevention into the urban planning in Catalonia, and it is corresponding to the legal study for the identification of geological risk (EIRG in Catalan). Therefore, it is a typified study used in the first stage of urban planning that concludes in a hazard preliminary assessment based on the qualitative criteria of experts. The EIRG conducts a local multi-hazard analysis at a local scale (from 1:5,000 to 1:2,000), which includes information and recommendations derived from the landslides inventory and susceptibility. The study runs in two levels, the first is focuses on finding the present hazard phenomena that may affect the studied urban area, which necessarily includes photo interpretation and field work to landslides inventory and susceptibility determination in broad sense. The second level focuses on hazard has been detected and a preliminary hazard assessment it is carried out (in a qualitative way) to set up the necessary recommendations to avoid this risk or reduce it.

Results: The risk assessment is carried out at a basic level. In this way, it is distinguishing the areas of low hazard, where it is easy to set up simple preventive measures and the land uses are not particularly limited, from the medium and high hazard areas that requires a land uses limitation based on a hazard quantitative analysis and zoning. With this staggered scheme, the systematic requirement to take geological risk into account in urban planning is met and analysis efforts are modulated so that they are dedicated to where they are really needed.

Conclusions: The guide provides a clear definition of the scope and goals of geological risk studies with a view to prevention in the field of urban planning. The Guide sets up a method for a qualitative risk assessment with clear criteria

P4.37

RISK MANAGEMENT FOR LANDSLIDES CAUSED BY EXTREME RAINS IN THE CITY OF AREQUIPA IN PERU

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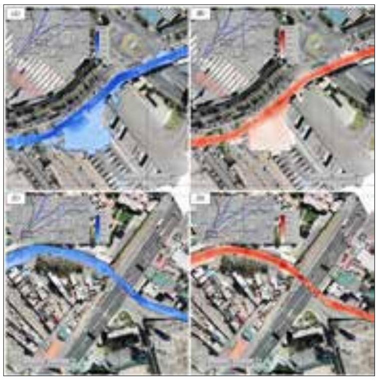
Purpose: These floods aggravate the situation of the population due to little or no territorial planning because there are no basic studies on hydrometeorological events in the city of Arequipa by government entities. These floods generated economic losses exceeding S/.350 million, and more than 80 thousand people were affected by torrential rains in 2013 due to a rainfall of 124.5 mm.

The flood of February 8, 2013



Risk map for a 100-year return period

Methods: The frequency of these events has increased with the time and that is the reason why rainfall thresholds have been created with their identification together with a 42- year register (1981 - 2022). For the hydrological model, the authors used the highest 24-hour precipitation data from the SENAMHI's stations (National Service of Meteorology and Hydrology of Peru) to obtain the liquid hydrograph for different return periods. Soil mechanics studies were also carried out to determine the rheological parameters of the non-Newtonian flow and then calibrate through historical events in a hydraulic model. Finally, cartographic maps were prepared to evaluate the vulnerability and high-risk areas of flooding.

Results:

Gorge	Flow max (m^3/s)	C_d	Flow (m^3/s) for different return periods (years)				
			TR=5	TR=25	TR=50	TR=100	TR=200
Del Pato	Water Flow	-	7.0	24.9	34.7	45.3	56.4
	Mud Flow	1.23	8.6	30.6	42.7	55.7	69.4
	Debris flow (Takahashi formula)	-	15.9	46.8	61.8	77.4	93.5
San Lázaro	Water Flow	-	15.9	46.8	61.8	77.4	93.5
	Mud Flow	**1.14**	**18.2**	**53.5**	**70.6**	**88.5**	**106.9**
	Debris flow (Takahashi formula)	2.44	38.7	114.0	150.5	188.5	227.8
Venezuela	Water Flow	-	10.0	23.9	31.0	38.6	46.5
	Mud Flow	**1.14**	**11.4**	**27.3**	**35.4**	**44.1**	**53.1**
	Debris flow (Takahashi formula)	1.21	12.1	28.9	37.5	46.7	56.2
Los Incas	Water Flow	-	22.2	69.6	93.1	117.7	143.1
	Mud Flow	**1.14**	**25.4**	**79.6**	**106.4**	**134.5**	**163.6**

*C_d: Thickening factor.

Conclusions: The hydrological modelling analysis was made for the gorges of the study: Del Pato, San Lazaro, Venezuela and Los Incas. The calibration of the sample was carried out considering the records of historical events between 1981 - 2022 (42 years), characterizing 24-hour maximum rainfall (15,340 pieces of information) with an “extremely rainy” threshold (99 percentile) which happens approximately every five years in the city of Arequipa. The behavior of water flowing through analyzed channels show critical depth and velocity, which cause undermining and erosion besides overflow and flood areas due to extreme rainfall, which is becoming more frequent. To answer this high risk in the city of Arequipa, we proposed energy dissipation systems such as staggered falls at bridges and retaining walls. We recommend preserving surveying points established by ANA (National Water Authority) in the higher parts of the gorges. These points have become relevant to Arequipeans as an educational tool to point out dangerous inhabiting areas near riverbanks. Due to extreme events occasioned by rainfalls, we strongly encourage different public institutions (Municipalities and Regional governments) to do appropriate city planning.

P4.38

RISK MANAGEMENT FOR LANDSLIDES CAUSED BY EXTREME RAINS IN THE CITY OF AREQUIPA IN PERU

Joel Ccanccapa Puma, Alejandro Víctor Hidalgo Valdivia
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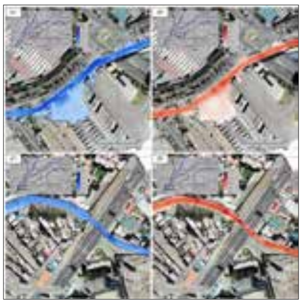
Purpose: These floods aggravate the situation of the population due to little or no territorial planning because there are no basic studies on hydrometeorological events in the city of Arequipa by government entities. These floods generated economic losses exceeding S/.350 million, and more than 80 thousand people were affected by torrential rains in 2013 due to a rainfall of 124.5 mm.

The flood of February 8, 2013



Risk map for a 100-year return period

Methods: The frequency of these events has increased with the time and that is the reason why rainfall thresholds have been created with their identification together with a 42- year register (1981 - 2022). For the hydrological model, the authors used the highest 24-hour precipitation data from the SENAMHI's stations (National Service of Meteorology and Hydrology of Peru) to obtain the liquid hydrograph for different return periods. Soil mechanics studies were also carried out to determine the rheological parameters of the non-Newtonian flow and then calibrate through historical events in a hydraulic model. Finally, cartographic maps were prepared to evaluate the vulnerability and high-risk areas of flooding.

Results:

Gorge	Máximo flow (m^3/s)	C_d	Flow (m^3/s) for different return periods (years)				
			TR=5	TR=25	TR=50	TR=100	TR=200
Del Pato	Water Flow	-	7.0	24.9	34.7	45.3	56.4
	Mud Flow	1.23	8.6	30.6	42.7	55.7	69.4
	Debris flow (Takahashi formula)	1.68	11.7	41.8	58.2	76.0	94.6
San Lázaro	Water flow	-	15.9	46.8	61.8	77.4	93.5
	Mud flow	1.14	18.2	53.5	70.6	88.5	106.9
	Debris flow (Takahashi formula)	2.44	38.7	114.0	150.5	188.5	227.8
Venezuela	Water Flow	-	10.0	23.9	31.0	38.6	46.5
	Mud Flow	1.14	11.4	27.3	35.4	44.1	53.1
	Debris flow (Takahashi formula)	1.21	12.1	28.9	37.5	46.7	56.2
Los Incas	Water Flow	-	22.2	69.6	93.1	117.7	143.1
	Mud Flow	1.14	25.4	79.6	106.4	134.5	163.6
	Debris flow (Takahashi formula)	1.52	33.8	106.1	141.9	179.4	218.1

Conclusions: The hydrological modelling analysis was made for the gorges of the study: Del Pato, San Lazaro, Venezuela and Los Incas. The calibration of the sample was carried out considering the records of historical events between 1981 - 2022 (42 years), characterizing 24-hour maximum rainfall (15,340 pieces of information) with an "extremely rainy" threshold (99 percentile) which happens approximately every five years in the city of Arequipa. The behavior of water flowing through analyzed channels show critical depth and velocity, which cause undermining and erosion besides overflow and flood areas due to extreme rainfall, which is becoming more frequent. To answer this high risk in the city of Arequipa, we proposed energy dissipation systems such as staggered falls at bridges and retaining walls. We recommend preserving surveying points established by ANA (National Water Authority) in the higher parts of the gorges. These points have become relevant to Arequipeans as an educational tool to point out dangerous inhabiting areas near riverbanks. Due to extreme events occasioned by rainfalls, we strongly encourage different public institutions (Municipalities and Regional governments) to do appropriate city planning.

P4.39

ESTABLISHMENT OF MOUNTAIN DISASTER PREVENTION COUNTERMEASURES THROUGH LANDSLIDE RISK ASSESSMENT AROUND MOUNTAIN WIND POWER GENERATION SITE

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Purpose: The series of extreme weather events in recent years has caught the world's attention. The Intergovernmental Panel of Climate Change (IPCC) has reported a study to limit the global average temperature rise, and one of its contents is the expansion of new and renewable energy. Recently, solar power generation facilities and wind power generation facilities have been expanding in Korea, and most have been installed in mountainous areas. The installation of renewable energy facilities is an important task to respond to climate change, but its collapse accidents and disasters cause damage to people's lives and properties. Therefore, when large-scale renewable energy facilities are installed in mountainous areas, it is necessary to evaluate the risk of disasters and establish a disaster prevention measure plan for expected disasters.

Methods: Disaster risk assessment was performed for mountainous areas where large-scale wind power generation facilities are to be installed. Field surveys such as surface geological survey, refraction survey were conducted focusing on the slope of the point where the windmill generator is to be installed. And the possibility of slope collapse during the dry season, rainy season, and earthquake was evaluated through slop stability analysis. Based on these research results, it is possible to establish the disaster prevention measure plan. The study area was divided into three basins considering the watershed. Based on the characteristics of mountainous terrain, geology and forests, the assessment of vulnerability of landslide and debris flow in mountainous basin units was suggested. In order to establish a in-situ investigation, analysis and evaluation plan for potential mountain disasters, we selected vulnerable mountainous basins for potential mountain disasters through analysis of vulnerability to mountain slope and stream.

Results: In the mountain disaster vulnerability assessment, it was analyzed that the possibility of landslides and debris flows rapidly increased due to the artificial slopes in the mountains and changes in the water system in the mountain basin due to the creation of the slopes due to the construction of wind power generation facilities in the mountain. Therefore, it is necessary to establish and apply active disaster prevention countermeasures by evaluating the vulnerability of potential mountain disasters.

Conclusions: It is necessary to identify the cause of mountain disasters by conducting a basic investigation using geo-spatial information and a detailed investigation of vulnerable areas on the potential risk of mountain disasters in the basin through the application of the concept of the mountain basin unit. In particular, if the facilities and residences are located around the mountain basin of wind power generation facilities, an overall mountain disaster prevention plan that reflects the results of the vulnerability assessment should be established through the analysis of the extent of damage caused by landslides and debris flows.

P4.40

DEBRIS FLOWS RISK ANALYSIS IN THE GIAMPILIERI AND BRIGA RIVER BASINS (SICILY, ITALY)

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Purpose: The Ionian side of the Peloritani mountains (Sicily, Italy) has experienced considerable urban development since the post-Second World War period and is highly prone to landslides. The area is characterized by the presence of an urban fabric concentrated in the east coast, where important linear infrastructures (roads, motorway, railway, water and gas pipeline, power and communication lines) are located. The Giampilieri and Briga basins, 15 km south of Messina, extend for 20 km2 and in recent years have been affected by major landslides events (March 25th, 2007, October 1st, 2009, March 1st, 2011). The objective of the study was a detailed GIS-based analysis of the local debris flows risk conditions.

Methods: The hazard assessment was conducted starting from an inventory dataset of hundreds of debris flows triggered by the heavy rains occurred on October 1st, 2009. For a selection of 50 initiation areas, the propagation areas were identified through the application of a specific runout GIS toolset based on the geometric approach. Such specific runout GIS tools largely facilitated the hazard analysis that required the execution of numerous algorithms in sequence to achieve the identification of the landslide path and the runout distance from several potential initiation areas. The analysed territory has been discretised by distinguishing areas with different susceptibility to be reached by the mobilized material. The runout hazard mapping was also performed considering the spatial distribution of the speed of the mobilized mass along the path and consequently the kinetic energy and destructive capacity. The level 3 of the Corine Land Cover was the basis for the discretization of the exposure. Further detailed information was taken from the Regional Technical Map (1:10,000) of the Sicily Region, about buildings of public interest and electricity grids, and from Open Street Maps about road network and railway. Approximately twelve classes of different types of exposed elements were classified: continuous and discontinuous urban fabric, buildings of public interest (hospitals, schools, town halls, military areas, churches), industrial areas, public sports and equipped green areas, cultivated and wooded areas, pastures and shrubs, roads, railway, power lines and gas pipelines. A relative value was assigned to each class of exposed elements based on qualitative evaluations. Similarly, a different degree of relative vulnerability was attributed to the exposed elements based on the different expected response of each class to the stresses induced by the debris flows phenomena.

Results: Through a qualitative risk evaluation matrix, the analysis has allowed to evaluate a different risk level to an asset located immediately at the base of a steep slope down where a debris flow may occur, from that of another asset placed at the limits of deposition area. The semi-automatized process developed appears particularly useful to implement tools devoted to regional planning and (pre) early warning system design.

Conclusions: Thanks to the use of public datasets, it can be exported successfully to other context and Countries where decision-makers are committed in landslides risk assessment.

P4.41

PHYSICAL VULNERABILITY MAPPING OF DEBRIS FLOW IN URBAN AREAS OF BUSAN, KOREA: A HAZARD LEVEL-BASED RAINFALL APPROACH USING RAINFALL THRESHOLDS, SUSCEPBILITY MAPS, AND VULNERABILITY CURVES

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Purpose: With regards to the content of the paper, the main objective is to produce a physical vulnerability map of debris flow in urban areas of Busan, Korea using rainfall thresholds, susceptibility maps, and vulnerability curves. This is important due to the increasing risk of slope disasters in mountainous regions caused by urbanization and overpopulation, particularly in South Korea during the rainy season from June to September.

Methods: The approach used in the study involves the use of statistical methods to compute rainfall thresholds based on different hazard levels for predicting landslides, using data from 288 landslide occurrences between 1999 and 2022. From this, rainfall thresholds for each hazard level of None, Watch, Warning, and Alarm 4 levels were proposed. The study also developed combined landslide susceptibility maps according to hazard level-based rainfalls using both physical and statistical-based models. Debris flow of high potential areas were selected using the combined susceptibility and geomorphological characteristics. The source areas of debris flow were extracted from the high potential areas which were then used to calculate the propagation and hazard intensity. In addition, a vulnerability curve was developed by analyzing 27 debris flow cases from 2011 to 2020 and collecting data on reinforced and unreinforced structure damage. Back-analysis of debris flows was performed through numerical analysis using Flow-R, and the impact pressure on each structure was calculated. The vulnerability curve was determined using sigmoid function, with the Avrami equation being utilized. This resulted in the calculation of affected buildings of debris flow using the propagation results of debris flow.

Results: Finally, the vulnerability index (ranging from 0 to 1) was categorized and evaluated based on the degree of damage to the building. According to the vulnerability index, it was classified as Complete (>0.8), Extensive (0.6-0.8), Moderate (0.3-0.6), and Slight (>0.3), and a vulnerability map of the study area was produced and evaluated. It is important to note that vulnerability assessment was carried out in the unit of census in Busan, and among a total of 2,221 census in the alarm stage of hazard-level rainfall, Slight was classified into 238, Moderate 347, Extensive 625, and Complete 1,011.

Conclusions: In terms of the potential impact of the techniques proposed, they have the potential to make a significant contribution towards protecting human lives and minimizing property damage caused by debris flow in urban areas of Busan, Korea. Furthermore, these methods may serve to mitigate the risk of landslides, and the proposed process may be utilized as crucial analytical data for assessing vulnerabilities and risks.

P4.42

SEMI-QUANTITATIVE VULNERABILITY OF SLOPE-UNITS IN TERMS OF BUILDING AGGREGATION FOR POTENTIAL LANDSLIDE RUNOUT

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Purpose: The mountainous terrain and highly weathered and fractured rocks contribute excessive mass wasting in Nepal Himalaya. Damages by landslides and debris flow to residential buildings are very common causing loss of lives. Therefore, it is important to analyze the potential damage to residential buildings that may be caused by landslides and their propagation. This study presents assessment of landslide vulnerability based on slope units under a scenario of data scarce in Sindhupalchok District, Nepal.

Methods: A physical vulnerability assessment was implemented by overlaying the landslide runout zone onto the area of the potentially affected buildings. This study was performed in three steps: (1) landslide susceptibility mapping to identify probable landslide source areas using combination of deep neural network and pseudostatic model; (2) runout assessment, using Flow-R, was performed to identify the potentially affected areas; and (3) physical vulnerability assessment was performed using a probabilistic method.

Results: For the physical vulnerability mapping, only building outlines were considered as an element at risk. Other building parameters, such as height of building and resistance to landslides, were not taken into account due to a lack of data. The unit area for the vulnerability assessment was defined by using slope-unit concept. The essential parameters i.e. velocity and travel angle were calculated using back-propagation approach for 35 prominent landslides which showed average velocity at 10.3 m/s and average travel angle at 13.02°. Total 97046 numbers of buildings in total were identified on a Google Earth image acquired in 2020; manual digitization was performed to vectorize the building outlines, which were stored in a GIS database. Finally, 2236 buildings were identified in the potentially affected area.

Conclusions: Physical vulnerability assessment is based on either a very detailed field inventory of building characteristics or expert judgments. In contrast to previous studies, this study presented a simple methodology under a scenario of scarce data.

P4.43

LANDSLIDE DISTRIBUTION ON NEPALESE HILL ROADS: ROLE OF EXISTING CONSTRUCTION PRACTICES AND CHALLENGE FOR SUSTAINABLE DEVELOPMENT

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Purpose: Landslides are major instability problems on hill roads of Nepal. Topography, slope orientation, lithology, geological structures, rainfall, groundwater conditions, and existing road construction practices are the principal attributes for such landslide occurrences. In Nepal, roads are being constructed by three (i.e., federal, provincial, and local) governmental levels frequently without sound engineering geological investigation. Consequently, such roads have triggered many mass movements. In this study we carry out the time series analysis for the distribution of landslides along some road corridors of Nepal.

Methods: For this purpose, we investigated and collected the information on road construction time and landslide events from published journals, reports, newspapers, and online sources spanning from different time. The various attributes were evaluated using a model based on a time series decomposition analysis; temporal, seasonal and residual. It is further tuned by Temporal Convolution Neural Network. The evaluation of the result are done by Mean Square Error.

Results: The analysis of aforementioned attributes shows that the road construction practice of leaving bare cut slopes without any support seems to be a major landslide-triggering factor during the monsoon season.

Conclusions: The study also demonstrates an increasing trend of landslide occurrence on hill roads of Nepal that have been constructed without sound engineering geological investigation and appropriate design.

P4.44

THE RISING RISK OF SETTLEMENTS ON LARGE SLOW-MOVING LANDSLIDES

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Purpose: The risk of large slow-moving landslides with human settlements catastrophically failing is a Black Elephant1. While significant progress has been made in our ability to widely detect and monitor landslide motion, our understanding of the interaction between urbanization on slow-moving landslides is in its infancy stage2. We are aware that an underestimated cascade seismic and hydrological forcings could drive settled large slow-moving landslides to catastrophic failure with devastating consequences2. This is a Black Elephant with disaster risk that has neither been quantified, nor widely acknowledged2. We investigate the expansion of settlements on large slow-moving landslides at a global scale and explore drivers that could determine where exposure is rising. Our results aim to direct research attention towards the identification, acknowledgement, and mitigation of increasing risks of such catastrophic failures.

Methods: We compiled a global catalog of 6,791 large DSGSDs and slow-moving landslide polygons (Area > 0.1 km2). Combined with data from the DLR's World Settlement Footprint Evolution3, the settlement areas and anthropogenic interaction on these large landslides between 1985-2015 were quantified. We extracted hydro-environmental information of the basins containing these landslides from the HydroATLAS and mountain range locations from the GMBA Mountain Inventory. Bayesian multi-level general linear regression models were used to investigate the probability of observing the 30-year expansion rates on the settled large landslide areas in our catalog. Our strategy was to explore the influence of anthropogenic and environmental drivers in the hydrological basins as candidate predictors.

Results: We detected 485 large slow-moving landslides in our catalog that interact with settlements located across 15 countries and 14 mountain ranges. We found 70 large landslides with settlements expanded by at least 10% in the last 30 years. We have observed that the 30-year expansion ratios in our catalog showed similar behavior to their corresponding basin population density at a country-level.

Conclusions: We find a significant rise of exposure in Turkey and China, while Italy and Japan show significantly lower 30-year expansion ratios. Settlements on large landslides in the mountain ranges of Tian Shan, the Anatolian Highlands and the South China Mountains expanded more rapidly over the past 30-years. Our results identify drivers of rising exposure on large slow-moving landslides that pose Black Elephant risks to settlements across the world.

Fig. 1. Global distribution of large landslides and the occupancy ratio of settlements present on more than 20% of the landslide area in 2015 (color bar), and the 30-year expansion ratio from 1985 (symbol size).

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P4.45

LANDSLIDE HAZARD MAPPING IN DOI PUI VILLAGE, CHIANG MAI, THAILAND

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Purpose and Methods: We have been conducting a project to evaluate the risk of landslides in the mountainous area of Chiang Mai. The results of the topographical and geological surveys show that Doi Pui Village is located on the moving body of a large-scale landslide and is surrounded by a steep slope composed of head scarps (Figure 1). At present, the entire area of the landslide is not moving, so it is considered stable. On the other hand, our topographical and geological surveys show that the village is at risk of small-scale landslides, rockfalls, and debris flows. Therefore, we made a multiple landslide hazard map. This presentation shows the landform and geological evidence of this hazard map.

Results and Conclusions: At Location. 01, the boundary between the large-scale landslide area (shown in red lines) and the non-landslide area can be observed. Many cracks can be seen in the rock mass of the landslide area, and the cross-section of the slip faces can be seen. At Location. 02, the talus formed by the supply of rocks and soils (weathered materials of rocks) from above the slope. Talus deposits here indicate that small-scale landslides will continue to supply rocks and soils from above the slope. There is another disaster potential here. Since the deposits are not consolidated, the deposits themselves may move due to small-scale landslides. Areas at risk of such disasters are shown in yellow in Figure 1. At Location. 03, massive boulders that fell from the head scarp are observed. The existence of these boulders shows that this site has a possibility that such a rockslide will occur in the future. The dangerous area of rockfall is indicated by a purple dashed line in Figure 1. At Location. 5, sediments mixed with stone and soil are observed. This sediment consists of a debris flow deposit, and it can be seen that the debris flow deposit reached this position from the upper part of the slope. The risk area of debris flow is indicated in orange in Figure 1.

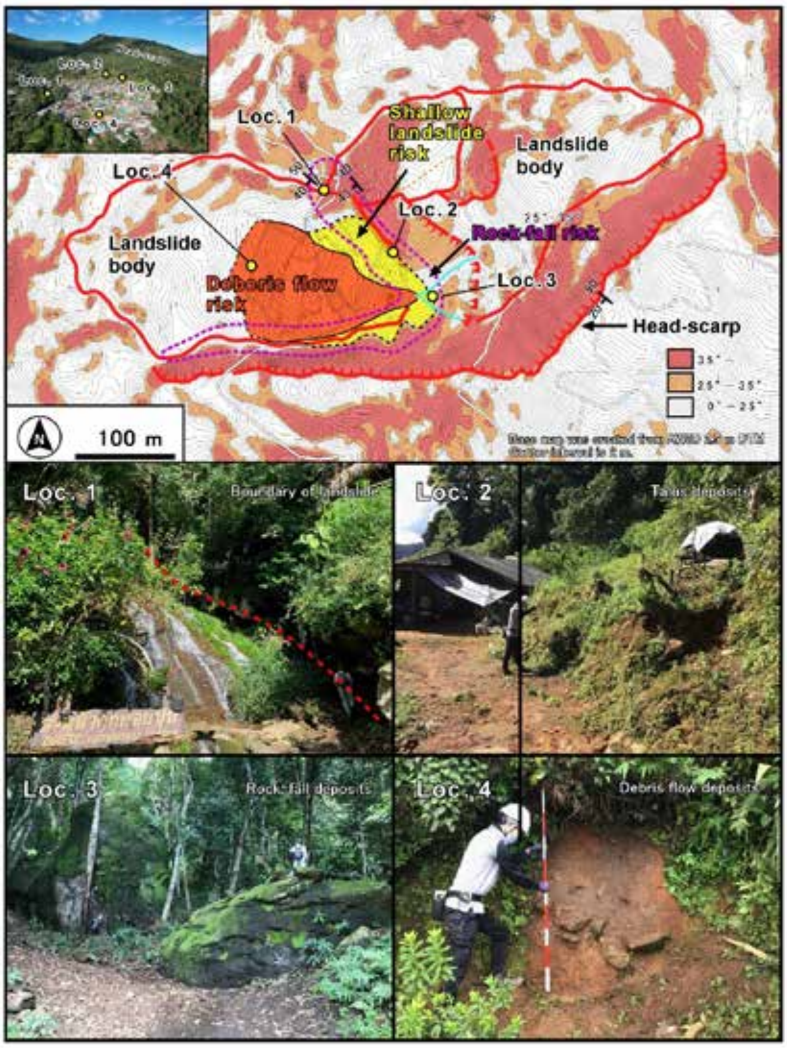

Fig. 1: Landslide hazard map in Doi Pui Village, Chiang Mai, Thailand.

P4.46
MULTIDISCIPLINARY APPROACH IN EVALUATING HYDROGEOLOGICAL RISK AFFECTING LINEAR INFRASTRUCTURES: STRATEGIES FOR RISK DEFINITION AND MITIGATION

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Purpose: Hydrogeological risk mitigation represents one of the major challenges in Italy, as almost the 90% of Italian Municipalities is potentially affected by water-related disasters and recent climate changes seem to increase this percentage. Therefore, the maintenance and management of linear infrastructures is necessarily related to the development of risk mitigation strategies. In 2020, a task force has been conceived to define an approach to deal with this problem. The task force, a team of almost 20 professionals, is based on a multidisciplinary approach: experts in geology, engineering geology, structural, civil, hydraulic engineering, topography, remote sensing work together to achieve the same goal: hydrogeological risk reduction and mitigation to acceptable values.

Methods: A list of areas where a potential risk (landslide, flood) could affect the railways/motorways is defined and organized in a list of priorities in terms of risk to the infrastructures. Following this defined order, the task force acts on specific subsequent steps:

1. Literature review: collection of all the information about the identified area and about the phenomena affecting or potentially affecting the infrastructure, such as existing cartography, reports of eventual events occurred in the past (newspapers, web etc.), scientific publications, available data (as data acquired by optical and radar satellites).
2. Field survey: a team composed of a geologist, a geotechnical engineer and a hydraulic engineer goes to the field to preliminary identify the effectiveness of the hydrogeological risk and its potential influence on the infrastructure.
3. Topographic relief: high resolution topographic reliefs are acquired by both airplane and UAV based lidar platforms.
4. Geological and geomorphological investigation: this is a crucial step, where the geologists define the effectiveness of specific risk affecting the infrastructure in terms of hazard and vulnerability, by using all the acquired information and documentation to study the phenomena and implementing specific field surveys and reliefs. If necessary, a survey campaign supports this step, with boreholes and geophysics campaigns to better investigate the phenomena and its spatial extension. A thematic cartography is produced during this step.
5. Definition of risk mitigation strategies: evaluation of possible structural and/or non-structural measures to reduce the hazard and the vulnerability of the infrastructure to the occurrence of hydrogeological phenomena.

Results: The conception of a task force made by experts of different disciplines aims at reducing hydrogeological risk to acceptable values. By working on almost 80 case studies per year, the task force produces a high number of projects both based on structural and non-structural measures (structural actions and monitoring activities related to early warning systems). The actual implementation of the proposed measures could strongly reduce the hydrogeological risk on the linear infrastructure, reducing the percentage of damage, the costs of reconstruction and strongly reducing risk to people.

Conclusions: As hydrogeological risk is a crucial problem in Italy, the proposed measures aim at reducing its impact on linear infrastructures, using an integrated approach. The conception of a dedicated task force made by different professionals is reducing potential risk to acceptable values, by implementing structural and/or non-structural measures.

P4.47

A NATION-WIDE EVALUATION OF THE INDIRECT IMPACTS OF HYDRO-GEOLOGICAL EVENTS ON LOCAL ECONOMIES

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Purpose: The objective of this work is a nation-wide analysis on Italian firms, to identify and quantify the indirect impacts that hydro-geological phenomena have on the local economy of the territories struck by severe events.

Methods: The analysis is based on advanced statistical correlations between econometric indicators and a dataset of severe events. Econometric indicators include revenues, number of employees, total factor productivity, and share of intangible assets. These data were retrieved from official governmental sources. Concerning hydro-geological events, we used a geodatabase compiled by an automated web datamining procedure based on a semantic algorithm, which provides the timing and location of harmful events. These datasets cover the period from 2010 to 2020, with a spatial detail at the municipality level. First, we use a staggered diff-in-diff approach to assess the probability of firms to exit the market after being hit by a severe event. Afterwards, for the survivor firms, we investigate the dynamic changes in econometric indicators after they are hit.

Results: We discovered that “hit” firms have +4.8% probability of closing down if compared with firms that were not hit in the same year. Survivor firms are affected in terms of reduction of revenues (-3.5%) and employment (-1.7%). These effects are not homogeneous: the impacts are statistically more significant for micro-small firms and for those located in rural areas.

Conclusions: The direct impacts of hydro-geological events can be quantified in terms of deaths and economic damages, but the indirect effects that such hazards exert on the local and national economy are less understood. With this study, for the first time a nation-wide quantitative evaluation of indirect impacts (in terms of reduction of employees and reduction of revenues) is carried out at the firms’ level, using Italy as a case of study. These findings can be useful to improve traditional quantitative risk assessment studies and to address mitigation and recovery policies.

P4.48

A WEB APPLICATION FOR FIELD DATA COLLECTION AIMED AT LANDSLIDE-INDUCED DAMAGE ASSESSMENT

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Purpose: Landslide-induced damage assessment is an essential instrument for planning mitigation measures and policies. The recent literature reveals a growing interest in the use of state-of-the-art approaches and tools for field data collection to quantitatively assess landslide impacts, vulnerability, and risk. This contribution intends to present and discuss the results of a dual field data collection conducted by both using an approach based on visual reconnaissance and digital mapping and a web application leveraging mobile technologies. Both approaches have been employed to collect data in the aftermath of an intense weather event that occurred in September 2022 in Marche region, Central Italy.

Methods: The systematic landslide reconnaissance field survey has been carried out within 1 month after the weather event. Detected landslides were reported (on site) on Google Earth and then controlled and edited in the office by the expert geomorphologists. Contemporary, a concise web application has been designed and developed to rapidly collect essential data on landslides location, characteristics, and impacts in the event aftermath. Survey forms have been conceptualized and implemented in a web application by means of KoboToolbox, a free and open-source suite of tools for data collection and analysis. Questions include fields dedicated to the description of the event characterization in terms of its basic modes of motion and involved material, fields to collect the landslide GPS position and geometry, and fields to record information on exposed and damaged assets. Surveys were conducted by multiple teams, each led by a geomorphologist experienced in landslide mapping. Data collection was often performed using the two different approaches, simultaneously.

Results: During the field surveys, information on more than 1600 landslides were collected and for around 400 of them the information was collected using both the mapping approaches (Donnini et al. 2023; Santangelo et al. 2023). Benefits of the data collection performed through the web application include: (i) real-time data collection and sharing, so that data can be analysed in near-real time for prompt decision-making and response; (ii) resilience to network failures; (iii) multimedia capabilities, allowing the capture and storage of photos and videos for an a posteriori quantitative evaluation of the damaged assets. Major limitations of the web application can be found in the uncertainty possibly due to the GPS receiver's accuracy and to the system's usability for field mapping purposes. Despite a minimum level of technical skills required to handle the web application, this sampling approach might result in sampling bias, affecting the reliability of the data collected.

Conclusions: Outcomes suggest that, despite some limitations, the web application might represent a valuable tool for a rapid landslide mapping and damage reporting even if a comparison with field mapping approach based on Google Earth highlights issues concerning the spatial representation and accuracy of the collected information.

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P4.49

SEAMOUNT INSTABILITIES OF THE MALLORCA CHANNEL (WESTERN MEDITERRÁNEAN)

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Purpose: The geological study of the Ses Olives, Ausias March and Emile Baudot seamounts and adjacent areas located in the Mallorca Channel (Balearic Promontory, western Mediterranean) has been carried out in order analyze the quaternary geomorphological evolution related to continental slope and seamount instabilities.

Methods: For this purpose, multibeam bathymetry and backscatter data as well as high-resolution parametric profiles have allowed us to identify several morphological features of different scales associated to gravitational and erosive-related processes.

Results: Major morphological features characterized are slides, slide scars, mass-transport deposits (MTDs) as well as different gully-systems affecting seamounts flanks. Slide scars have been recognized at the top and flanks of the seamounts as well as at the adjacent areas in the central basin. They show diverse geometries that can be affected by scarp faults and pockmarks developing multiple steep scars with lengths of up to 15 km. MTDs are identified throughout the entire study area and present mostly elongated morphologies. They extend between 1 and 11 km from the scars, and locally present perpendicular trajectories between the different sedimentary bodies. They generate seafloor reliefs of more than 20 m and up to 50 ms thick in the seismic profiles, identifying stacks of, at least, three different episodes. In some cases, the movement of the displaced mass in the subsurface have produced a high deformation of the materials located above. Gullies are mostly located on the flanks of the Ausias March and Emile Baudot seamounts, as well as in the north central flank of Ses Olives. They have a rectilinear shapes, although with an irregular distribution, with orientations that vary from NW-SE to NE-SW for the Ausias March and Emile Baudot, respectively, and SO-NE in Ses Olives. They develop small slides and bedforms of turbiditic origin.

Conclusions: The integrated analyses have allowed us to calculated that the area affected by sedimentary instabilities is around 10% of the study area (500 km2) mainly related to tectonics and fluid expulsion processes. This study will offer new insights and understanding of the geological hazard scenario in this sector of the Balearic continental margin.

P4.50

GRASP SUBMARINE LANDSLIDES: COMBINING GEOMORPHOLOGICAL PARAMETERS AND GEOSTATISTICAL ANALYSES TO ASSESS GEOHAZARDS IN THE ITALIAN SEAS

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Purpose: This work aims to broaden the knowledge about mass-wasting events in the offshore environment, using geomorphological parameters in order to determine the predisposing and triggering factors and consequently using geostatistical analyses apply the results on hazard assessment. Submarine landslides are widespread events occurring across both active and passive continental margin that may have serious consequences on coastal areas and offshore infrastructures. The genesis and evolution of landslide are controlled by different geological factors which may be considered as predisposing factors (e.g., seafloor morphology, lithology, type of sediment, presence of fluid or weak layers) and triggering factors (e.g., earthquakes) (Masson et al. 2006). The landslide hazard assessment lies in estimation of where, when (or how frequently) and how large they will be in a given area (Guzzetti et al. 2006). In offshore environments this is particularly difficult to assess because the information that we acquire are few and usually not well distributed as onland, due to the difficulty to have direct observations and to costly data acquisition. For these reasons in terms of geohazard assessment the offshore and onshore environments do not have the same abilities to predict the occurrence of the failures, therefore, a geostatistical approach on very large number of features could probably be the most realistic way to solve the gap of information and knowledge.

Methods: The Italian continental margins may provide an excellent playfield with a key role to study submarine landslides because these features have been identified and mapped in different morpho-tectonic and sedimentary contexts (e.g., accretionary prism, volcanic edifices, foredeep continental slope, upper slope in front of large deltas…). A first Atlas of high-resolution seafloor morphologies and features indicative of geohazard along the Italian margins has been produced within the MaGIC project (Marine Geohazards along the Italian Coasts) funded by the Italian Civil Protection (DPC) that the whole Italian marine scientific community collaborated on.

Results: Building on this knowledge a new methodological approach will be defined, using morphological features to classify, hierarchize and quantify parameters that will be used to apply geostatistical techniques. These analyses hopefully will provide a new approach to define predisposing and triggering factors that control the occurrence of the submarine mass-wasting events.

Conclusions: With this new approach that combines geomorphological evidence and geostatistical methods we aim at:

- Improve the knowledge about submarine mass-wasting.
- Try to fill the gap between offshore and onshore landslides knowledge.
- Determine the geohazard-susceptibility along the Italian continental margins in order to mitigate the risk for the coastal communities and marine infrastructure

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Key words : Submarine landslide, Geomorphometry, Hazard assessment, Geostatistic

P4.51
GEOHAZARD ASSESSMENT OF SUBMARINE LANDSLIDES ALONG THE SQUILLACE CANYON HEADWALLS, OFFSHORE CALABRIA (IONIAN SEA)

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Purpose: The Ionian Calabrian margin is marked by the presence of numerous widespread landslides, in some cases related to the Squillace submarine canyon enlargement. Despite the young age (Pleistocene), this submarine canyon is very large due to retrogressive failures that characterise its headwalls in the direction of the coast, especially where the deliver from the "fiumare" are important.

Some of the observed landslides occur very close to the coastline (up to a few hundred metres), with different dimensions and complex geometries. We aim in extracting new information regarding their dynamic and evolution along the multiple headwalls of the examined canyon, by adding to the morphometric analysis the results of statistical analysis. The overall purpose of the study is to bring new insights about the causal factors and assess the potential geohazard that such retrogressive failures may represent today for coastal areas and infrastructures offshore Calabria.

Methods: Morphometric analysis represents a valuable tool in studies related to the marine environment, as often bathymetry data are the only available data. From this type of data, statistical analysis of geomorphic attributes may be performed to correlate parameters that define the characteristics of the examined features, as this type of analysis is based on the relationship between chosen attributes. The geophysical datasets used in this study were acquired during three research campaigns that took place along the Ionian Calabrian margin from 2005 to 2015. These acquisitions to derive DTMs with a 10x10 m, 20x20 m and 50x50 m grid size, that were used for the evaluation of the geomorphic attributes in the statistical analysis. New geophysical data using ROV and AUV will be acquired in June 2023 during the ERODOTO (funded by Eurofleets+) campaign along the Squillace canyon headwalls, this will allow to examine the morphologies of the failures at an unprecedented resolution.

Results: Morphobathymetric data revealed numerous landslide scarps on the continental slope in a depth range from -200 m to -950 m, that mainly follows the slope dip orientation. The scarps located on the upper part of the continental slope show smaller but more arcuate geometries, while those on deeper portions of the slope exhibit a larger lateral extension. The statistical analysis will allow to correlate the geometry attributes of the landslides, their location and connection to geological processes, thus providing a key to develop an evolutional model of the retreating headwall failures.

Conclusions: The integration of seabed mapping and statistical analysis may represent a valid new approach in geohazard assessment-related studies, particularly in determining the possible pre-conditioning factors of submarine landslides. This new approach can prove to be particularly useful in assessing the occurrence of hazards related to the Squillace headwall enlargement and to his retrogressive activity in direction of the coasts where coastal infrastructures as ports, highway and railway are located.

P4.52
SUBMARINE SEDIMENTARY INSTABILITIES ON THE PALOMARES CONTINENTAL MARGIN (W MEDITERRANEAN)

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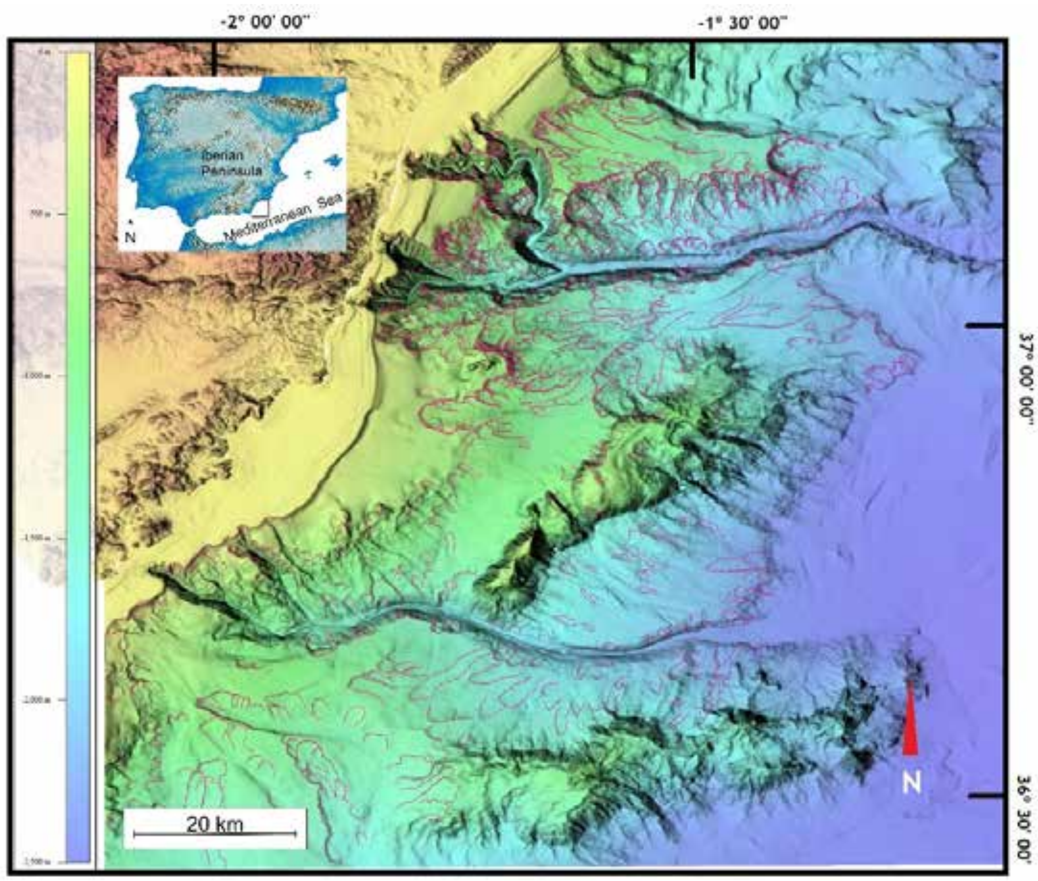
Knowledge of the distribution of landslides at a regional scale, i.e. magnitude-frequency, constitutes a valuable step towards assessing landslide-related geohazards. In marine settings, such studies are also important although the availability of accurate inventories remains poor because of the commonly low accessibility of high-resolution data at regional scales.

The analysis of medium and high resolution (50m and 15 m respectively) multibeam bathymetric data has allowed to build a regional inventory from the Palomares Continental Margin, located in the Iberian Mediterranean margin. This continental margin encompasses different tectonic and sedimentary features at various scales defining a heterogeneous, abrupt and irregular physiography. Morphological highs, prominent submarine canyons and morphosedimentary features associated with contour currents and sedimentary instabilities are the main features defining the geomorphologic evolution of the margin.

Mass-wasting affect more than 821 km2 and mobilized about 10.34 km3 of sediment along the continental slope through 937 events. Each event has been defined by its scar and head area but other parameters such as scar length and sinuosity, regional gradient, scar height and gradient have been included in the inventory. Statistical analysis of the results obtained revealed that the cumulative distribution of the landslide size area may be described by both inverse power and log-normal distributions.



Scars identified in the study area

P4.53

LANDSLIDES ON MID-OCEAN RIDGES: THE BIGHT FRACTURE ZONE (N ATLANTIC)

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Purpose: The Bight Fracture Zone is among the most conspicuous geomorphic feature of the Mid-Atlantic Ridge. A recent oceanographic cruise was carried out to know the geologic processes occurring in that fracture zone and related triangle-shaped wrench basins that develop at both sides of the mid-ocean ridge, at water depths between 767 and 3061 m. In this regard, this works analyses the morphology, seismic facies and deposits paying special attention to the occurrence of landslides.

Methods: Dataset used in this study comprises multibeam bathymetry and parametric ultra-high-resolution seismic profiles that were simultaneously recorded.

Results: The fracture zone is characterized by large W-E strike-slip faults that offset a series of ridges and troughs probably related to N-S trending volcanic lineations. This trending is roughly parallel to the pattern of magnetic anomaly affected by the fractures system. Active seismicity occurs along the nearby expansion ridge with magnitudes up to 5.7 and hypocentres at a mean depth of 10 km. The wrench basins are infilled by wedge-shaped deposits thickening far from the present-day mid-ocean ridge. They comprise well-layered deposits displaying a wavy configuration with vertically aggrading pattern, which seems to mimic the undulating configuration that the old volcanic ridges and troughs create at the seafloor. The occasional presence of individual layers with stronger reflectivity and high lateral continuity are also identified. The strata pattern shows that the lateral continuity of the well-layered deposits is interrupted by several interbedded chaotic and transparent wedge- and tabular-shaped bodies with irregular and erosive boundaries. These bodies reach lengths up to 12 km long and to 45 m thick. Their vertical stacking is characterized by an upward scale change being the large ones buried and the smaller ones at the present-day seafloor.

Conclusions: Despite being in a deep-sea environment under low-energy sedimentation dominated by biogenic oozes and muddy contourites locally shaped by the Iceland-Scotland Overflow Water (ISOW), the imaging of the seafloor and subbottom show a striking reworking sedimentary activity by local energetic mass-wasting processes that leads to the deposition of mass-flow deposits and turbidites on their wave flanks and troughs. The spatial and temporal distribution of these deposits seem to involve a lateral relocation of their activity. This activity seems to decrease with time and away from the mid-ocean ridge. This fact points out that the mass-wasting activity would be mainly triggered by the interplay between the seismicity of the opening of the ridge, whose influence decreases as the basin progressively moves further from the ridge, and the oversteeping seafloor of the ridge flanks.

P4.54

CHARACTERIZATION OF THE SUBMARINE S- EUFEMIA SLIDE (CALABRO-TYRRHENIAN MARGIN, ITALY) THROUGH THE ANALYSIS OF MORPHO-BATHYMETRIC AND SEISMIC DATA

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Morpho-bathymetric and seismic reflection data collected along Calabro-Tyrrhenian margin have evidenced several mass-wasting features affecting this area. In this work, we present a detailed morpho-stratigraphic analysis of a fresh-looking submarine landslide in the upper continental slope of the S. Eufemia Gulf (here named S. Eufemia landslide), very close to recent fault scarps displacing the post-LGM deposits and sometimes cutting up to the seafloor. The S. Eufemia landslide is located 10 km offshore from the southern Calabria coastline, just below the shelf break between 185 and 345 m water depth, affecting a total surface of approximately 4 km2. The slide scar has a width of approximately 2300 m and length of approximately 700 m long and it is bounded by 20-40 m high headwall scarps, having an overall staircase-like pattern due to the presence of discontinuous and detached sediment slabs, with heights of 10-15 m and slope gradients of 25°-34°. Landslide deposits are well-detectable on high-resolution bathymetric data, at depths greater than 300 m, where a marked decrease of slope gradients to values < 2° is present. Landslide deposits cover a surface of about 2.5 km2, with a vertical relief of 5-10 with respect to the surrounding seafloor. The depositional area can be divided into three sectors characterized by different morphological features (pressure ridges, rafted blocks, etc.,) and seismic facies. Based on the integrated analysis of morpho-bathymetric, high-resolution seismic data and seafloor sampling, we discuss the failure and post-failure behavior of such landslide, as well as we attempt to constraint its age and possible relationship with tectonic features and historical earthquakes, including the catastrophic 1905 earthquake. Because of its fresh-looking morphology and well-defined geometry, the characterization of this tectonically-related landslide can be also used as reference model to compare similar features elsewhere.

P4.55

A SPATIO-TEMPORAL APPROACH TO EVALUATE ROCKFALL EXPOSURE IN MALLORCA (BALEARIC ISLANDS, SPAIN)

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Purpose: The development of preventive methodologies to detect and map geohazards and evaluate their potential impacts is essential for risk management planning in vulnerable areas. This work presents a new approach to analyze rockfall exposure from both a physical and social perspective. The proposed approach was applied in the Tramuntana Range (Mallorca, Spain), a mountainous area characterized by a steep orography in high geological complexity. These conditions lead to frequent rockfalls, many of which have caused significant damage to the road network in recent years. These damaging rockfalls are not only related to an increase in the occurrence of rockfall events, but also to an increase in rockfall exposure due to population growth and land-use intensification.

Methods: The proposed methodology comprises four steps: (i) data collection and processing, (ii) selection of the indicators, (iii) normalization of the indicators and determination of their specific weight, and (iv) calculation of the Exposed Elements Index (EEI) through multiple-criteria decision analysis. The resulting EEI values were then used to obtain a map of exposed elements by municipality, previously fitting the values to a beta distribution function. Before applying the methodology, the available data on land use and population/housing were collected, as well as several doctoral theses concerned with the analysis of tourist seasonality in Mallorca. Following, seven indicators related to environmental, infrastructural and social factors, were considered to evaluate exposure. These indicators were used to derive seven normalized indexes. Subsequently, the weight of each single indicator was calculated using the harmonized average. The overall indexes of social, infrastructural and environmental exposed elements were then obtained as the weighted average of the corresponding single indicators. Finally, to calculate the EEI, a heuristic method was applied. Thus, the weight assigned to each indicator primarily reflects its influence on the short-term rockfall impacts on the island's society and economy.

Results: As a result of the methodology, three exposure maps were obtained taking into account the tourist seasons by municipality. As expected, according to the results obtained, the level of exposure increases during the high tourist season (which represents, in contrast, the period of least occurrence of rockfalls). Figure 1 shows the difference between the EEI values obtained in the average season (TM) and in the low season (TB) for each municipality, as well as the difference obtained between the high season (TA) and the low season for each municipality.

Conclusions: The methodology proposed in this work, developed in the framework of the project RISKCOAST (SOE3/P4/E0868) funded by the Interreg Sudoe Programme, can be considered a novel contribution to the improvement of the understanding of rockfall exposure within the 13 municipalities distributed throughout the Tramuntana Range. Note that if both a rockfall susceptibility map and a vulnerability (of the element at risk) map are available, the exposure maps obtained in this work could be further used to evaluate rockfall risk.

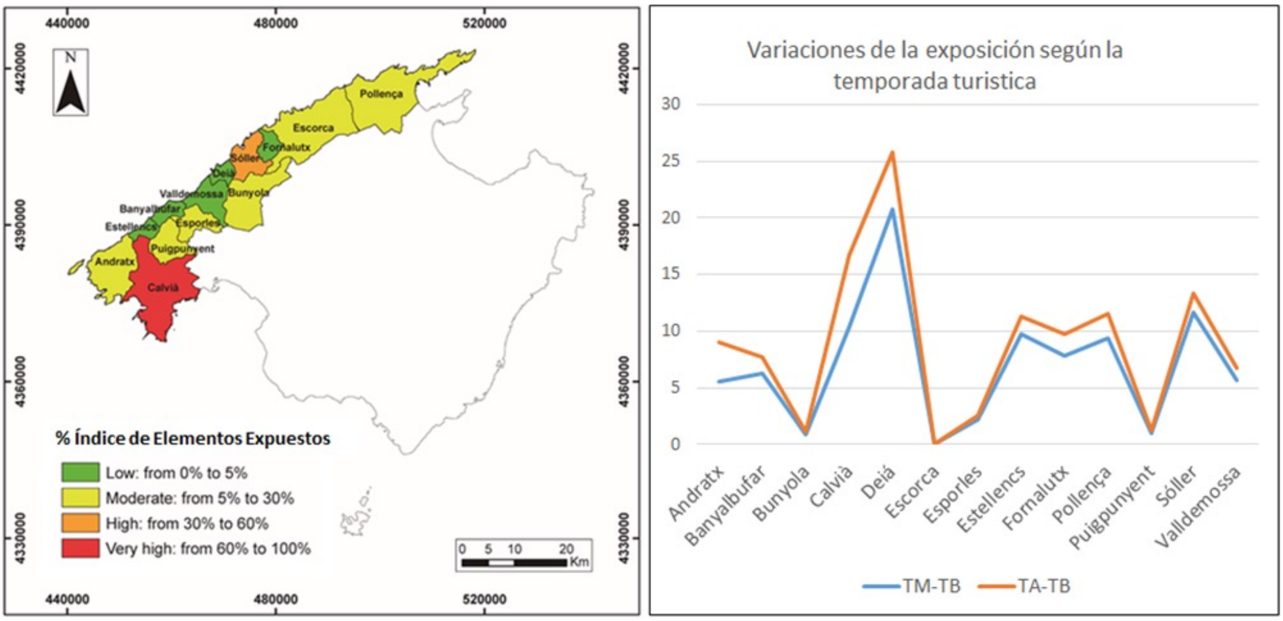

Fig. 1: EEI results for the high season, and a chart with the differences in EEI according to the tourist seasonality in each municipality of the Tramuntana Range.

P4.56

EFFICIENT INTENSITY MEASURE FOR LANDSLIDE VULNERABILITY ASSESSMENT OF HILLSIDE BUILDINGS

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Purpose: The present study aims to propose an efficient intensity measure (IM) for landslide vulnerability assessment of two commonly observed reinforced concrete hillside building configurations, i.e., step-back (SB) and split-foundation (SF).

Methods: The efficiency analysis of various prospective IMs, namely, flow depth (h), velocity (v), flow density (ρ), dynamic pressure coefficient (α), Froude number (Fr), overturning moment (hv), momentum flux (hv2), moment of momentum flux (h2v2), hydrodynamic impact pressure (ρv2), and static pressure (ρh) is performed to propose an efficient IM for hillside buildings. The efficiency of an IM is evaluated by assuming a power-law relationship between IM and engineering demand parameter (EDP), expressed through a logarithmic transformation as follows:

$$\ln(EDP_i)=a+b\ln(IMi)+\varepsilon_i \quad (1)$$

where a and b are the regression coefficients and ε_i represents the error between the computed and estimated values of EDPi. The standard deviation of the error term (σ_ε) is used as a measure of the efficiency of any IM. Further, the proficiency ($\zeta = \sigma_\varepsilon/b$) test[1] is also performed for the IMs showing higher efficiency to get a conclusive insight. Smaller values of σ_ε and ζ imply more efficient and proficient, respectively, IM. The efficiency analysis is carried out for two scenarios, i.e., landslide-only (LS-only) and landslide following earthquake (EQXg-LS). The uncertainty in the soil properties is considered based on laboratory experiments[2] and existing database of landslide events. Nonlinear-static analyses are performed to obtain drift response of the hillside buildings under landslide loading. Whereas in the case of landslide following earthquake, the nonlinear time history analysis is performed, for a set of earthquake ground motions scaled to a predefined intensity (X), to obtain an earthquake-damaged model prior to landslide loading phase.

Results: The linear regression curve is fitted between various IMs and peak (among all floors) interstory drift ratio (IDR) of 4-story SB and SF buildings. Values of σ_ε and ζ for the IMs showing higher efficiency are summarized in Table 1. The efficiency of all the other considered IMs is found to be lesser than those reported in Table 1. It can be observed that the efficiency of hv is more than h2v2 and ρv2 for both landslide-only and landslide following earthquake scenarios.

Table 1. Regression coefficients obtained from linear regression between ln(IDR) and various IMs.

Building model		σ_ε				ζ			
		SB building		**SF building**		**SB building**		**SF building**	
Loading scenario		LS-only	EQ0.25g-LS	LS-only	EQ0.25g-LS	LS-only	EQ0.25g-LS	LS-only	EQ0.25g-LS
IMs	hv	0.0886	0.1469	0.0982	0.0992	0.0962	0.1277	0.1053	0.1061
	h^2v^2	0.0886	0.1469	0.0982	0.0992	0.1925	0.2553	0.2105	0.2122
	ρv^2	0.0954	0.1549	0.1067	0.1082	0.2096	0.2712	0.2317	0.2354

Conclusions: The overturning moment (hv) is the most efficient IM for landslide vulnerability assessment of undamaged and earthquake-damaged hillside buildings.

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P4.57

A NONSTATIONARY EXTREME VALUE APPROACH TO ESTIMATING THE TEMPORAL PROBABILITY OF RAINFALL INDUCED SHALLOW LANDSLIDES UNDER CLIMATE CHANGE

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Purpose: Rainfall has been considered the primary trigger of shallow landslides since rainfall infiltration causes an increase in pore water pressures and subsequently, initiates the occurrence of shallow landslides. Therefore, rainfall patterns such as intensity and frequency are important factors that affect shallow landslide occurrences; and changes in rainfall patterns can significantly affect landslide frequency and magnitude. Consequently, since climate change may alter rainfall patterns, climate variation may also strongly influence the landslide hazard. Especially, the temporal probability of landslide occurrence largely depends on climatic conditions, and can therefore change, as climate variations may significantly affect the frequency of trigger events. In recent years, the temporal probability has been estimated using historical rainfall records, rather than historical landslide records, which is extremely difficult to obtain. However, in the previous research for the evaluations of temporal probability using rainfall records, changes in rainfall patterns could not be included; that is, historical rainfall records were taken into be a stationary process. It means that statistical properties of the observed data, such as their probability distribution parameters, are constant and do not change over time. Therefore, these approaches cannot respond to nonstationary rainfall characteristics, caused by climate change.

Methods: In this study, we propose a new approach based on a nonstationary generalized extreme value distribution (NS-GEV) for estimating the temporal probability of future rainfall-induced landslides when the rainfall data show nonstationary characteristics. Extreme value analysis (EVA) enables inferences about probabilities of future extreme event occurrence based on historical records. Although EVA for historical records of extreme precipitation has been used to evaluate the temporal probability of rainfall-induced landslides, the analysis has generally adopted the stationary assumption. Therefore, in this study, a process for evaluating the occurrence probability of rainfall-induced landslides based on nonstationary extreme value analysis was developed.

Results: Using the proposed nonstationary approach, the temporal probability of landslides was calculated for future periods and the results were compared with those based on a stationary approach. Results of this study showed that the nonstationary probability values of landslide occurrence were greater than the values from stationary analysis. In other words, future rainfall-induced landslide probability could be significantly higher than probability calculated under the stationary assumption since the stationary analysis was unable to respond to the increasing trend in local rainfall data observed in the study area. Consequently, it appears that ongoing climate change will affect the evaluation of rainfall-induced landslide hazards.

Conclusions: The process of landslide temporal probability assessment involves considerable uncertainty caused by climate change. Consequently, it is important to examine carefully the nonstationary characteristics involved in rainfall data. In this study, the analysis procedure for landslide temporal probability was proposed by applying NS-GEV model. The nonstationary approach shown to be an effective approach to the incorporation of the projected climate variations; therefore, it should be considered to reflect the impacts of climate change in any landslide hazard analysis.

THEME 5

CLIMATE CHANGE, EXTREME WEATHER, EARTHQUAKES AND LANDSLIDES

P5.1
INTERCONNECTION OF LANDSLIDES' ACTIVATION WITH MEDITERRANEAN CYCLONES. THE CASE OF CEPHALONIA ISLAND, GREECE

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Purpose: From 17 to 19 September 2020 a Mediterranean Cyclone (MEDICANE), dubbed Ianos by the National Observatory of Athens (NOA), affected Greece, causing a series of landslides nationwide. One of the most affected heavily areas was the island of Cephalonia. The accumulated 24-hour rainfall recorded on 17 September at Antipata meteorological station, located at the North of the island, was 644.7mm. This value is the highest ever recorded during a medicane and one of the highest in Greece [1]. Nowadays medicanes are rare meteorological phenomena. Due to climate change, this is expected to change, as there is an increasing trend in their occurrence in the Eastern Mediterranean and an increasing trend in their intensity and duration in the whole Mediterranean region [2,3], posing a serious threat for local communities, concerning the landslides' activation. The present work aims to: (a) Identify and map the landslides that were activated by Ianos, to provide an integrated landslide inventory; (b) Correlate the inventory with local hydrological and geological characteristics, to reveal critical insights about the landslide activating mechanism.

Methods: This was achieved by processing data acquired from different sources such as satellite images, open-access sources, and previous studies [3–6]. SNAP software was used to process the Sentinel-1 images.

Results: Figure 1 illustrates a landslide, which was identified by using Sentinel-1 and Google-Earth images. Subsequently, the landslides inventory map (LIM) illustrated in Figure 2 was created, consisting of over 600 landslides, the majority of which were debris flows and rockfalls. Most devastating debris flows were recorded in Assos and Fiskardo villages. By using satellite images, the extend of the debris flow in Fiskardo village, was estimated to be almost 600m long. Rockfalls also affected many areas, causing the disruption of the road network and the collapse of the Chimoniko bridge.

Fig. 1: Landslide's Identification with Google-Earth before (a) and after (b) Ianos.

Figure 2: Cephalonia/Ianos landslides inventory map.

Conclusions: The created LIM could be a valuable and useful tool for authorities contributing to their efforts to apply suitable precaution measures. It was also revealed that besides precipitation, the lithology, the unfavorable slope's angle, and the proximity to faults, were the most critical causal factors.

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P5.2
POTENTIAL INSTABILITY OF GAS HYDRATE VS CLIMATE CHANGE: CHILEAN MARGIN CASE STUDY

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Purpose: Many scientists worldwide are working to better understand the onshore and offshore distribution of gas hydrate and its stability conditions. Gas hydrate is being studied for a variety of reasons; for example, hydrate accumulations can store large amounts of natural gas that could be a potential energy resource. Gas hydrates located offshore play an important role primarily because of the critical issues of their potential decomposition. Indeed, any change in pressure and/or temperature conditions can lead to dissociation of gas hydrates. This already happened in the past and may happen in the near future, as modelled in several studies, since the recent assessment of the International Panel on Climate Change confirms that climate change may lead to an increase in ocean temperatures and sea levels. The release of large amounts of natural gas into the water column could affect the marine ecosystem and have significant impacts on benthic organisms. In addition, methane is an important greenhouse gas and could enter the atmosphere after its release into the ocean, which could lead to a positive feedback on global warming, as previous studies have shown, although this is still controversial in the scientific community. In this context, the Chilean margin is a natural laboratory where studying these phenomena.

Methods: In recent years, the link between gas hydrate and submarine slides has been widely studied. Excess pore pressure has been identified as a key parameter for assessing slope instability. Shear strength increases significantly in hydrate-containing sediments compared to hydrate-free sediments; during gas hydrate dissociation, the released gas could increase the local pore fluid pressure in the sediment. For this reason, the change in mechanical properties of marine sediments due to gas hydrate dissociation could lead to slope instability. The Chilean margin is very interesting from a gas hydrate perspective and is a natural laboratory to study the evolution and relationship between the gas hydrate system and natural phenomena. The presence of hydrate on this margin has been confirmed by several geophysical cruises. The seismic lines analysis allowed to identify the presence of gas hydrates and free gas in many places along this margin and the alteration of the pore fluid due to the possible hydrate dissociation.

Results: The reduction in porosity due to the presence of hydrate is associated with the slope to identify the area that is more sensitive in the event of natural or human activity-induced phenomena that could lead to gas hydrate dissociation and/or escape of the free gas trapped beneath the gas hydrate stability zone. Steady-state modelling has shown that climate change could lead to gas hydrate dissociation and consequent slope failure. This hypothesis is supported by the presence of high concentrations of gas hydrate near important seafloor slopes.

Conclusions: Dissociation of hydrate could alter the petrophysical properties of the subsurface, triggering slides that occurred in the past. Therefore, it is necessary to improve knowledge of the behavior of the gas hydrate system in response to complex natural phenomena before this important resource can be exploited.

P5.3
EFFECT OF WARMING SURFACE TEMPERATURE ON THE OCCURRENCE OF SOIL LANDSLIDES

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Purpose: Global Warming phenomena has caused changes in the Earth's climate and it shows a warming trend of 0.850C. Hence, many regions in the world are experiencing higher temperatures and variable precipitations including Sri Lanka. The effect of rising temperatures which has not yet been considered, could be another catalyst for creation of unstable landmasses in hilly areas. The aim of this study is to evaluate whether there is an effect of the increase of surface temperature on the occurrence of soil landslides in Sri Lanka.

Methods: Twenty such major landslides, which occurred in May 2017 in the Wet Zone hilly areas of Sri Lanka were selected. The study was carried out by implementing a historical data approach by comparing the catalogue of selected landslides with climatic records (rainfall, temperature, potential evapotranspiration and soil moisture) covering the last two decades. Data were acquired from both ground stations and publicly available remote sensing data. Water deficit conditions at each failure location were studied using a standard water balance equation, for twenty years prior to occurrence of failures.

Results: The results suggested that failure locations had experienced a dry period with high temperatures almost continuously for every year prior to the major failure. Water deficits had occurred every year in the months from January to March prior to the southwest monsoon rainfall during May. Their maximum (negative) values varied from -110.67 mm to -149.25 mm in the months from January to March respectively. Further, the monthly average temperatures were highest in the month of March. The failures occurred in the month of May in year 2017.

Conclusions: These warmer and drier atmospheric spells prior to the failure event could conduce to form desiccation cracks at failure initiation areas. They could enhance the infiltration capacity of rain water after a heavy precipitation event which would accelerate the development of pore-water pressures leading to a reduction in strength of the ground mass. Successive cycles of healing/ reopening of cracks which is brought about by seasonal variation of rainfall combined with rising temperatures may lead to form areas of reduced strength, which could cause failure to occur progressively and eventually leading to a major landslide.

P5.4

IMPACT OF EXTREME EVENTS RELATED TO CLIMATE CHANGE IN MONTAIN AREAS: PRELIMINARY RESULTS FROM THE ABRUZZO REGION (CENTRAL ITALY)

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Purpose: In recent years, scientific interest in the relationships between global warming-related disaster events and hydrogeological risk is increasing. Future climate predictions make it necessary to better understand the influence of climate on geomorphological processes such as landslides. Despite numerous studies on the subject, many aspects remain to be clarified. In recent decades, Italy has been the stage for hundreds of calamitous rainfall events, often followed by floods or landslide events that have had a significant impact not only in terms of human lives but also economically. This study aims to investigate the influence of extreme weather events on mountainous areas in theAbruzzo Region (central Italy). The aim is to understand how the variation in frequency, intensity and spatial distribution of extreme events and the modification of meteorological parameters can affect the natural environment and human activities.

Methods: Daily precipitation data were collected from 202 stations located within Abruzzo for the period 1918-2021. The data were statistically analyzed in order to identify "rare events." In detail, the percentile method was used considering that a rainfall event is defined as "rare" when it is rarer than the 90th percentile. Maps illustrating both the distribution of threshold values and the number of rare events within the region were created in GIS environment. Next, a database of landslide events was created by drawing from all available sources (Abruzzo, IFFI project, CNR). For each event, the type of landslide, date and geographic coordinates were specified (where available). With these data, the landslide density map was created through which the stations that fell in areas with values greater than 0.4 landslides/km2 were chosen. The closest station was then paired with each landslide. Finally, precipitation data up to 31 days before the landslide event were selected in order to compute rainfall thresholds by quantile regression method. In particular, the cumulative rainfall (total rainfall measured from the beginning of a rainfall event to the time of failure) and the duration of the rainfall period have been considered. Finally, all the maps and data obtained have been compared with the geologic and topographic maps in order to investigate possible relationships.

Results: Preliminary results indicate that:

i) "rare" events are concentrated in the Gran Sasso (eastern sector) and Maiella mountains and along the coastal belt. A small cluster is recorded at the western Abruzzo border;
ii) most of the "rare" events occur below 1000 m of elevation and affect flysch-like rock-types;
iii) there is no clear correspondence between "rare" events and landslides except in the coastal belt;
iv) rainfall thresholds seem to vary according to landslide type.

Conclusions: Although preliminary, this study has allowed the calculation of rainfall thresholds for Abruzzo, enabling the identification of critical areas where to focus by field investigation to define the landslides predisposing and triggering factors and the local-scale impact of climate variations. This will lead to the assessment of the susceptibility of the study area to geomorphological phenomena and a better land management and resilience policies with respect to climate change.

P5.5

ESTIMATING LANDSLIDE HAZARD AT THE REGIONAL SCALE CONSIDERING DISTINCT CLIMATE CHANGE SCENARIOS

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Purpose: Shallow landslides triggered by rainfall occur nowadays worldwide and will continue to occur in the future. However, ongoing climate change produces modifications in rainfall patterns that will be reflected in changing patterns of landslide activity, and thus in future landslide hazard. This research aims at evaluating landslide hazard at the present time and at the end of the 21st century, considering two climate change scenarios: RCP 4.5 and RCP 8.5. The study area is the Arrábida, a small mountain with a Mediterranean climate that spans 35 km across the southern part of the Lisbon Metropolitan Area (Portugal).

Methods: A statistical method (Information Value) was employed to evaluate the landslide susceptibility, using seven landslide predisposing factors and a landslide inventory comprising 4047 rainfall-triggered landslides occurred in the Lisbon and Tagus Valley region, which includes the study area. The landslide susceptibility model was validated using a sub-set of 197 rainfall-triggered shallow slides identified in the Arrábida in 2012. The exact dates for most of these landslides are unknown, but we assume that their morphological maintenance in the landscape is no longer than 20 years. Landslide susceptibility classes were defined based on the slope breaks of the prediction-rate curve. The future landslide activity was assessed considering the critical rainfall thresholds established for the Lisbon region by Vaz et al. (2018) and the projections of these thresholds for the end of the 21st century, for both RCP 4.5 and RCP 8.5 scenarios provided by Araújo et al (2022).

Results: We estimate for the end of the 21st century an annual average landslide affected area of 40,400 m2 and 34,600 m2, for RCP 4.5 and RCP 8.5, respectively, assuming a linear relationship between changes in rainfall occurrence and landslide affected area. These features compare with the 38,440 m2 yearly average landslide area estimated for the present time. The landslide probability was computed for each grid cell within each landslide susceptibility class. Nowadays, the annual landslide probability for each 10 m grid cell covered by the highest landslide susceptibility class is 0.407 and will increase to 0.427 in the end of the 21st century for the RCP 4.5 scenario. In the case of RCP 8.5, the same feature will decrease to 0.366.

Conclusions: Projecting future landslide hazard is a difficult task because of uncertainties related to climate change, but also because of uncertainties regarding the effects of changes on the rainfall patterns on the landslide activity at the regional scale. The assumption of the maintenance of the predictive capacity of each susceptibility class along time is an additional source of uncertainty of the model.

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P5.6

ROCK SLOPE SPATIO-TEMPORAL STRAIN EVOLUTION: FROM FIELD DATA TO NUMERICAL MODELING

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Purpose: Evaluation of the stress-strain in rock masses is a crucial step in the case of slope stability studies. The shallow rock slope surficial zone is highly affected by short-term (diurnal, annual) and long-term (global) temperature cycles, which leads to significant stress-strain field changes. These cycles can play a significant role in rock slope destabilization, eventually leading to a rock fall. However, in-situ monitoring is time demanding, expensive and can only provide point information about strain spatiotemporal behaviour. Nevertheless, these data can be used for the calibration of numerical models, which can represent the whole slope. This way, stress/strain evolution can be modelled in different scenarios, and the effect of future temperature changes on rock slope stability can be partially predicted.

Methods: In this work, we used field-gathered data from in-situ thermo-mechanical monitoring, to construct and calibrate numerical stress-strain models. Field data are represented by a 3 m deep temperature profile from the borehole probe, as well as air and surface temperature at the monitoring site "Pastýřská rock" (Figure 1) in Děčín (Czechia). These data we have used to determine the thermal conductivity and capacity of rock mass, using a simple 1D model. These variables, together with the mechanical properties of the rock mass detected with laboratory tests, allowed to define simplified thermo-mechanical models validated using field data from induction crack gauges. A complex 3D rock slope thermo-mechanical model were then defined. Using these, areas with high termally-induced stresses can be pointed out. Finally, by the introduction of possible future atmospheric temperature projections, the influence of these on possible rock slope destabilization can be evaluated.

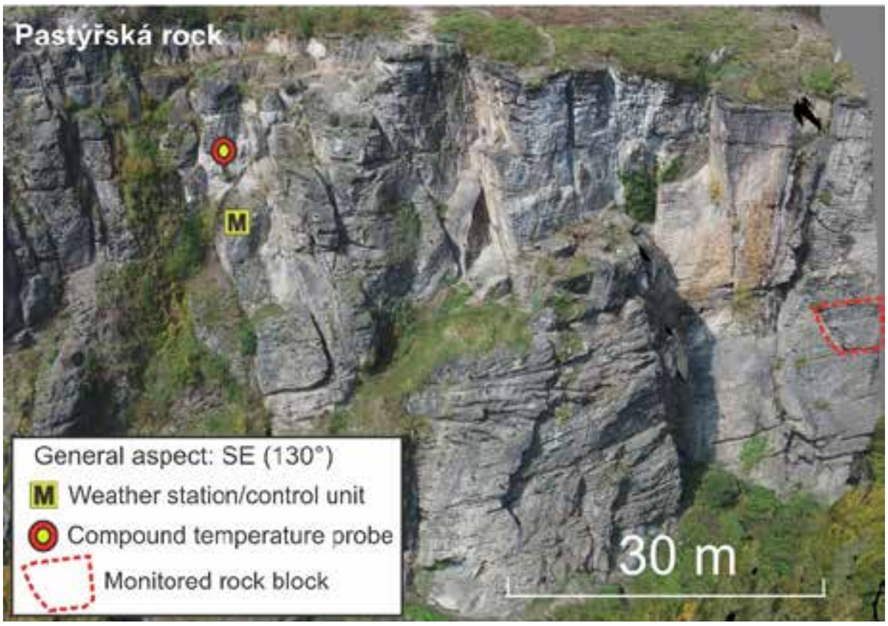

Fig. 1: Monitoring site "Pastýřská rock", placement of monitoring system main parts.

Results: The 1D models were constructed using 4-year long time series data from borehole temperature probe measurements. This model allowed to assess the best values of rock mass thermal properties, which were then used as input to the simplified 3D models. Their strain modeling performance was validated by comparing modelled and in-situ measured joint displacements. This way, we could have assumed, that the thermo-mechanical model reasonably matches real natural behaviour of rock slope. In the last step, a complex 3D model of the rock slope, including main discontinuity sets, was built to identify highly thermally stressed parts. Lastly, different temperature trend scenarios were analysed, to identify the impact of climate change to rock slope stability.

Conclusions: Our study shows the importance of including field-gathered data in the definition of stress-strain numerical models. This way, we can assume, that the model is representing the real rock slope behaviour as close as possible. By a combination of field monitoring and numerical modeling approaches, the thermally forced dynamic of rock slope can be described. By introducing expected future temperature changes, the effect on rock slope dynamic and possible destabilization in the future due to climatic change, can be explored.

P5.7
EXTREME DEBRIS FLOWS EVENTS RECORDED ON ROYA RIVER TRIBURATIES : WHAT CHALLENGES DOES THIS TYPE OF EVENT POSE FOR RISK MANAGEMENT?

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Purpose: In October 2020, the Atlantic storm « Alex » caused an exceptional "Mediterranean" episode in the coastal Alpines valleys of Roya and Var Rivers. This hydro-meteorological phenomenon generated local rainfall totals in excess of 600 mm (litres/m²), and led to geomorphological transformations of the slopes and river beds, partial destruction of the forest cover, and devastating floods. Post-event erosions and deposits could be subdivided into 4 categories, i.e. gully erosions and landslides, rockfalls, piles of cobbles and gravels. These sedimentary contributions changed the morphology of the Roya's river and its tributaries. The return time of these exceptional floods, which involve erosion processes and complex flows (torrential sludge and block transport), is poorly constrained. Moreover, this return time could change in a context of global warming of the Mediterranean Sea. This study aims to quantify the sedimentological processes of the Alex-related Mediterranean event and the identification of similar events in the sedimentary record.

Methods: With the idea of evaluating the hydro-geomorphological Alex event in a source-to-sink approach, the study starts with the creation of a GIS database gathering all the historical data (photos, writings, land registry). These data can show the evolution or past flooding in the valley and more recent data after the storm (location of landslides, types of landslides). The evolution of the active band of the Roya and tributary rivers, and eroded surfaces are being particularly studied. Stratigraphic and sedimentological cross-sections of flood deposits and first datation of past flood events by OSL (optically stimulated luminescence) were carried out. We present here results of remote sensing surveys (i) mapping landslide evolution since the Alex event and (ii) quantifying the geomorphological changes (volume of erosion) in two studies cases, namely the "Vallon de la Consciente" and the "Vallon de Dente", tributaries located in the upstream part of the Roya's valley.

Results: The sedimentary record investigated in the located areas includes several important hydro-geomorphological events (i.e. debris flows of similar magnitude to those triggered during the Alex flood), dated at (i)1500 +/- 30 BP (Before Present), (ii) 920 +/- 30BP and 760 +/- 30BP, and (iii) at 480 +/- 30 BP with deposits similar to storm Alex.

Conclusions: Preliminary age chronology of investigated debris flows made it possible to establish a return time of approximately 500 years for Alex-type events in the Roya valley. The last flood deposits comparable to those at Storm Alex date from the Little Ice Age. After the Little Ice Age, the climate warmed up, implying less erosion of the slopes and a progressive contraction of the river bed.

P5.8
RECONSTRUCTING CHANGES IN DEBRIS FLOW ACTIVITY ON ALLUVIAL FANS AT PLANSEE (TYROL, AT) USING AMPHIBIOUS METHODS

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The frequency of hazardous mass movements is strongly influenced by climate and seismic forcing. Rainstorms are a major trigger for shallow landsliding and debris-laden flows, and the magnitude and frequency of intense rainstorms is expected to increase in the European Alps. To find out how natural hazards respond to these changes and different climate scenarios, long-term records have to be investigated. Plansee (Tyrol, Austria) is surrounded by highly active alluvial fans and the lake sediments preserve a record of Holocene debris flow recurrence with varying intensity in the same catchment. The lake is located in the region of the Bavarian-Tirolian landslide cluster, a globally known hotspot of Late Holocene Alpine hazards. We investigate the history of debris-flow deposition on alluvial fans and their subaquatic deltas using sediment cores, LiDAR data, orthophotos and Electrical Resistivity Tomography. The sediment cores from the lake bottom reveal a total of 138 debris-flow induced turbidites within the last 4000 years. A constant background sedimentation with low debris flow rates contrasts to i) debris flow frequency increases interpreted as post-seismic landscape response and ii) a 7-fold increase in debris flow frequency between the periods ~1520 to 1920 CE and 1920 to 2018 CE. In this setting, fluctuations in debris flow activity are mostly controlled by few severe earthquakes and climate forcing. The long term record is complemented by terrestrial and floating cable Electrical Resistivity Tomography surveys, providing information on the total thickness of the alluvial cones and the underlying basal moraine. Air photography and LiDAR data is used to determine debris-flow volumes over the last decades and to provide information on catchment and system changes which influence debris flow recurrence.

P5.9

PROJECTIONS OF LANDSLIDE HAZARD ACROSS HIGH MOUNTAIN ASIA

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Purpose: High Mountain Asia (HMA) is a hotspot for landslide activity. The risk from landslides is likely to increase over the coming decades due to increases in extreme precipitation. Characterizing the distribution over time and space of the changes to hazard from precipitation-triggered landslides may help governments and other stakeholders prepare adapt to climate change in advance.

Methods: Statistically downscaled precipitation and temperature from a "large ensemble" global circulation model were used to generate a landslide hazard indicator with a daily 5-km resolution. The model was developed with machine learning from an ensemble consensus product that describes historical precipitation across HMA, with the Global Landslide Catalog supplying a target variable. In addition to precipitation, the model considers temperature, relief, soil, rock, and seismic factors. Landslide timing was summarized with a Markham seasonality index.

Results: Most mountain ranges will experience increases of roughly 20% from the period 2015-2020 to the period 2091-2100. The relative increases will be greatest in Tibet, while the absolute increases will be greatest along the Himalayan arc. Except for a narrow band of terrain in Pakistan, changes to the timing of landslide season will be relatively minor.

Conclusions: Landslide hazard is projected to rise in most of HMA by end of century. Even in locations where hazard may decline by 2100, increases may occur by mid-century. However, no major regime change is expected. Future research could target specific areas with high-resolution physically based models to verify these results.

P5.10

CHARACTERISE THERMAL PROPERTIES AND QUANTIFY NON-CONDUCTIVE HEAT FLUXES IN MOUNTAIN PERMAFROST

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Purpose: Permafrost is warming and thawing at a global scale because of climate change and this has consequences for slope stability. Despite numerous studies focusing on the evolution of permafrost, knowledge of the physical properties of frozen ground is based on a few in-situ measurements and laboratory experiments. There is a paucity of observations on water fluxes in permafrost, which are rapidly changing, due to active layer thickening, ground ice melt, talik formation and modified permeability. Particular attention should be given to changes in thermal regime, an indicator of water-induced permafrost degradation, which are currently inducing increasingly deep-seated slope instabilities.

Methods: In this study, we identify non-conductive heat flow in mountain permafrost as a potential proxy for water fluxes, using borehole temperature data. We quantify thermal diffusivity based on a linear regression between d2T/dz2 and dT/dt (Nicholson & Benn, 2012) and examine the temporal evolution of thermal diffusivity in mountain permafrost boreholes, using the largest mountain permafrost database worldwide, the Swiss Permafrost Monitoring Network PERMOS. Deviations from the regression line can be used as a qualitative indication of non-conductive heat fluxes. Following Petersen et al. (2022), the empirical estimation of thermal diffusivity based on multiple linear regression, with additional consideration of dk/dz. In addition to the described approach, we calculate conductive heat fluxes using analytical and numerical modeling. Given the one-dimensional heat conservation equation, the non-conductive heat flux is quantified using the difference between the observed and modeled temporal temperature change.

Results: Figure 1 shows preliminary results for the Murtèl-Corvatsch 2015 borehole with (a) an empirical estimation of the thermal diffusivity based on the simple linear regression and (b) depth profiles for the annual evolution of the thermal conductivities from 2016 to 2022 as well as coefficient of determination boxplots. While temporally steady values and high coefficients of determination arise at depths with stable conductive thermal regimes, large variations in thermal diffusivity and lower coefficient of determination values indicate a combination of conductive and non-conductive heat fluxes. These are likely indicators of water fluxes in the permafrost.

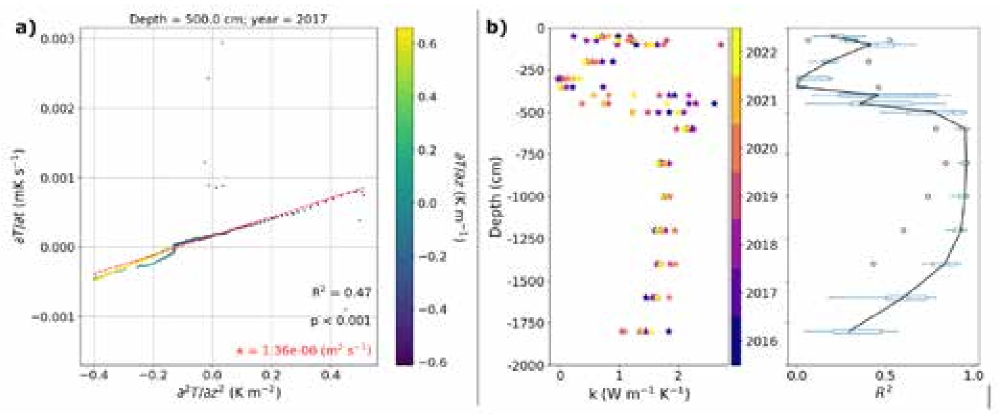

Fig. 1: Thermal characterization of the Murtèl-Corvatsch 2015 borehole. (a) Estimation of thermal diffusivity for a single year (2017) and depth (500 cm) and (b) evolution of thermal conductivity and coefficient of determination boxplots for the profile from 2016 to 2022.

Conclusions: The systematic analysis of the PERMOS borehole temperature data, with three independent methods, allows us to derive a well-constrained range for the thermal properties of mountain permafrost with different substrates such as talus slopes, ice-rich rock glaciers, and bedrock. From these preliminary results, we establish the possibility of further investigating non-conductive processes governed by thawing and/or water advection. Once concluded, this analysis will represent the basis for many other studies investigating the thermal and mechanical behaviour of mountain permafrost slopes.

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P5.11
CAN LONG RUNOUT LANDSLIDES WITH LONGITUDINAL RIDGES BE USED AS PALEOCLIMATIC MARKER IN ICELAND AND ON MARS?

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Purpose: Long runout landslides are some of the most enigmatic and catastrophic geological processes, which are ubiquitous in the Solar System. Much work has already been done to study the behaviour of long runout landslides and their associated longitudinal ridges, yet the origin of their hypermobility and the formation mechanism of the longitudinal ridges are poorly understood. Both the presence of glaciers and their retreat in response to climatic changes are suggested to play a crucial role in the development of large, catastrophic landslides. However, the causal and temporal relationship between the occurrence of long runout landslides with longitudinal ridges and glacial retreat remains unresolved.

Methods: Iceland is a unique region on Earth for its high spatial density of hypermobile landslides with longitudinal ridges, in areas that have experienced glaciation in the past. On Mars, numerous long runout landslides with longitudinal ridges are found where the presence of widespread glaciations has been suggested. Therefore, these locations are ideal sites to investigate the impact of glacial retreat in the development of long runout landslides with longitudinal ridges. In this work, we used a combination of interdisciplinary methods and approaches including remote sensing and photogrammetry in terrestrial and planetary environments, geomorphology and stratigraphy. The objectives are: 1) to understand whether Icelandic long runout landslides with associated longitudinal ridges can be used as good analogues of martian landforms, similar to other elements of the Icelandic landscape and their associated mass-wasting processes; 2) to determine the influence of glacial and paraglacial conditions in the development of long runout landslides with longitudinal ridges in Iceland and in selected martian regions.

Results: Here, we compared the morphological parameters of Icelandic landslides with martian landslides that are similar in length. We present detailed morphological observations of one Icelandic case study, the Dalvík landslide, and we compare it with morphological observations of analogue martian landslide deposits. Our results show that Icelandic long runout landslides share similar morphometric values and key features with martian analogue deposits, including splitting of longitudinal ridges and development of associated en-echelon features. Therefore, we conclude that Icelandic long runout landslides with associated longitudinal ridges can be used as good analogues of martian landforms. Additionally, in order to define the stratigraphic relationship between the long runout landslide deposits with longitudinal ridges and other sedimentary units, we conducted geological mapping in three study areas: 1) the Tröllaskagi peninsula, Iceland, on Earth; 2) west Coprates Chasma, Valles Marineris, on Mars; 3) Aeolis Mensae, on Mars. Here, we present preliminary results from the geological mapping, which will help in understanding the impact of paleo-environmental conditions on the formation of long runout landslides with longitudinal ridges.

Conclusions: Ultimately, a better understanding of the influence of climatic, geological, and environmental conditions in the development of hypermobile landslides will have implications for both terrestrial hazard assessment and reconstruction of extra-terrestrial paleo-environments.

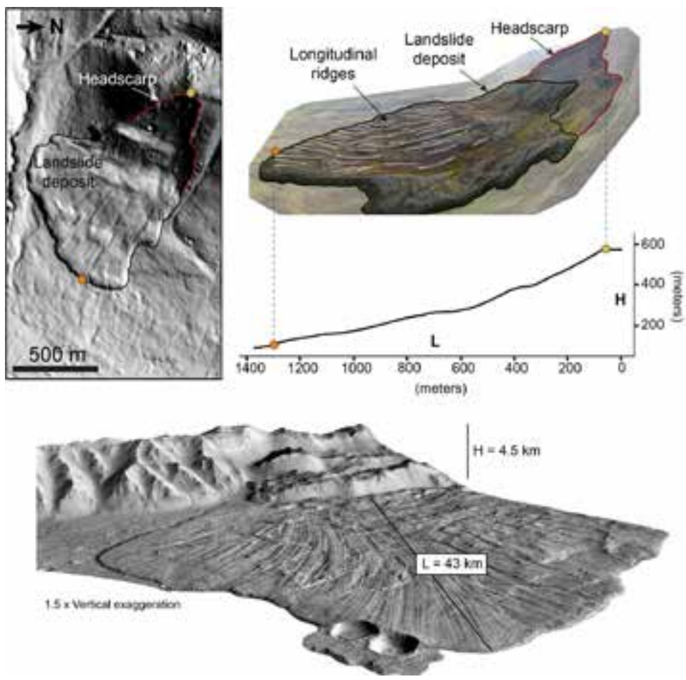

Fig. 1: Examples of Icelandic (top) and martian (bottom) long runout landslides with longitudinal ridges.

P5.12

FLOW BEHAVIORS AND BASAL NORMAL STRESSES OF ROCK-ICE AVALANCHES IN ROTATING DRUM EXPRIMENTS

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Purpose: Rock-ice avalanches have been found to move much further than rock avalanches, and their flow regime may change as the ice melts. While several reports have been published that investigate the deposition characteristics, high mobility, and hazard assessments of rock-ice avalanches, there is currently no systematic study on the flow regime evolution and the basal stress characteristics of these avalanches.

Methods: We conducted a series of rotating drum experiments in a temperature-controllable laboratory using different initial conditions (including ice content, particle size, base velocity, and volume of meltwater). To control the effects of meltwater, all the tests were carried out in temperature-controllable laboratories. The advantage of using a rotating drum is that it allows for continuous measurements over an extended period of time at a given flow velocity, thereby enabling observation of flow regime changes related to ice melting. Additionally, this device permits measurement and analysis of statistical data on basal normal stress of rock-ice avalanches through the use of a load cell at the base.

Results: Based on several dimensionless spaces, we discussed the geometric and kinetic similarities between drum experiments and natural events. The analysis indicates that, despite the more intricate flow behavior and dynamics of rock-ice avalanches, there is a certain degree of geometric and kinetic similarity between drum experiments and natural events. Subsequent results show that the average normal stress profiles vary significantly with the ice content and meltwater volume. Furthermore, the mean stress, , maximum stress, σ1%, and standard deviation, σsd, were used to quantitatively demonstrate how stress fluctuations are closely related to static loads of flow and particle interactions. At the grain scale, we determined that the particle agitation in the rock-ice avalanche is caused by intense collisions that depend on particle size, velocity, and fluid matrix.

Conclusions: The findings in this study provide quantitative data on flow regime and basal normal stress to help improve the understanding of rock-ice avalanche dynamics.

P5.13

INSIGHTS FROM MONSOON-TRIGGERED LANDSLIDE TIMING INFORMATION DERIVED FROM SENTINEL-1

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Purpose: Hundreds of landslides are triggered during the monsoon season in Nepal every year, which are significant in terms of both mass wasting and of the hazard they pose to communities. The locations and spatial extents of these landslides can be mapped with optical satellite images, but persistent cloud cover during the monsoon season prevents their timings from being constrained. The purpose of this work is to apply newly developed landslide timing techniques based on Sentinel-1 satellite radar image time series. With this timing information, we are able to (i) identify spatio-temporal clusters of landslides associated with cloudburst events and (ii) compare the timings of landslides triggered during the 2015 monsoon (which was preceded by an Mw 7.8 earthquake) to those triggered in subsequent years (2017-2019).

Methods: Sentinel-1 satellite radar images are acquired in all weather conditions every 12 days on two tracks globally. These images are sensitive to landslides, which alter the scattering properties and 3D shape of the Earth's surface. We applied a recently developed method which can assign 12-day time windows to around 30% of landslides in an inventory based on Sentinel-1 amplitude time series.

In order to associate landslide timings with specific peaks in rainfall, we used the NASA GPM-IMERG satellite precipitation product. We also employed a simple numerical model of soil water content through time to estimate the soil water content at the timing of failure. This was then used in the Factor of Safety equation to draw conclusions on hillslope strength.

Results: We were able to obtain timings for 306 landslides across 4 monsoon seasons in central and eastern Nepal using Sentinel-1 methods. From this we take two main results. First, we observed spatio-temporal clusters of landslides associated with specific peaks in rainfall in 2015, 2017 and 2019. Second, we observed that during the 2015 monsoon, landslides occurred much earlier and after less rainfall than in other years. A reduction in hillslope strength resulting from the preceding earthquake is required to resolve this in our modelling, for example a loss of cohesion in the range 1-5 kPa.

Conclusions: We have used Sentinel-1 time series to obtain landslide timings across central and eastern Nepal during the 2015, 2017, 2018 and 2019 monsoon seasons. From this new dataset, we have observed spatio-temporal clusters of landslides and tied these to specific periods of localised heavy rainfall. We have also established that the Mw 7.8 2015 Gorkha earthquake resulted in landslides occurring earlier and after less rainfall during the subsequent monsoon season.

P5.14

NUMERICAL CALCULATIONS AND SCENARIO RECONSTRUCTION OF THE FEBRUARY 7TH, 2021, CHAMOLI EVENT

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Purpose: The February 7th catastrophe in the Chamoli district of Uttarakhand India, was a complex event, which initiated as a massive rock-ice slide of 27 Mm3 at an elevation of nearly 5600 m a.s.l. This event impacted the catchments of Ronti Gad, Rishiganga and Dhauliganga valleys, cascading down-valley into a high magnitude, long runout debris flow. It also dammed rivers and led to formation of lake dams and destructed two hydroelectric projects enroute, causing hundreds of fatalities (ICIMOD, 2021; Thayyen et al., 2021). The event thus impelled scientists worldwide to recognize the fragility of Himalayan terrain under the prevailing changes in climate.

Methods: In the present study we try to reconstruct the cascade numerically and conceptually from the initial rock-ice slide to nearly 25 km downstream, until the Tapovan HEP, after which the flow deaccelerated. The runout trajectory was thus segmented into five major sections, based on: i) gradient changes; ii) observed flow physical parameters and channel characteristics; iii) erosion-deposition and entrainment; iv) runout rheology and behaviour. Next, the section wise peak velocity-discharge and energy was calculated, based on the fundamental Voellmy, Perla and Flow-R model. The erosion and deposition changes along the runout were analysed using satellite and field images. The results obtained were compared to better understand the velocity-energy changes along the longitudinal profile of the run-out, and to understand the time progress of event along the different sections.

Results: The calculated flow parameters, corresponded well with the proposed segmentation of runout trajectory and the sequence of events. The velocity and time calculated using Perla model were well validated as per the available seismic records (Tiwari et al., 2022). The discharge, energy values and the erosion-deposition changes presented, were also in-line with the available literature and explain well the proposed sequence of events.

Conclusions: Rockfalls, rockslides and rock avalanches occurring in glaciated environments and permafrost regions are characterized by their sudden and complex character, high magnitude-mobility and cascading secondary hazards. Their dynamics is controlled by interaction between the detached rock, the icy component, water interactions during all phases of motion, from initiation to final deposition (Sosio et al., 2015). This was evident in the case of Chamoli event, where the flow mobility enhanced progressively and by the presence of ice, snow, and water.

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P5.15

INVESTIGATING THE INFLUENCE OF WILDFIRE ON THE GEOTECHNICAL PROPERTIES OF SLOPING PYROCLASTIC SOILS

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Purpose: Enhancing the existing knowledge about the effects of wildfires on geotechnical properties of soils originated from pyroclastic airfall deposits of the Campania region (southern Italy), by providing a preliminary characterization of the changes in the physical-mechanical and hydraulic properties of the topsoils affected by three wildfires in 2019 and 2020. Post-fire rainfall-induced soil erosion processes occurred in the study sites. The study area is one of the most exposed to fast-moving landslides in Italy since it was affected by multiple events in the past, including the disaster of 5–6 May 1998. In the Authors' opinion, the research findings can be useful to improve the knowledge about mechanisms controlling post-fire erosion/shallow landslide responses in similar areas and to provide input data for implementing prediction models or planning in situ monitoring systems.

Methods: The procedure followed to investigate the fire-induced changes in key soil geotechnical properties consists of three main steps: i) remote sensing analyses for mapping and classifying the fire severity of the burned area; ii) in situ assessment of the fire burn severity and sampling activity; (iii) geotechnical characterization of both unburned and burned soil samples.

Results: The results revealed to be site-specific, mainly depending on soil characteristics and fire burn severity. Regarding the soil physical properties, no significant changes were found in the grain size distribution, soil organic matter, and specific gravity of burned samples compared to unburned ones. Moreover, the results from the direct shear tests demonstrated degradation of the soil mechanical properties because of the wildfires. A decrease in soil cohesion was observed due to fire burning and weakening of the root systems. We found that even a low burn severity fire can cause a decrease in soil cohesion. In addition, no significant change in soil friction angle due to fire was found. Regarding soil hydraulic properties, the burned samples exhibited soil water retention and hydraulic conductivity changes under both saturated and unsaturated conditions. Specifically, a decrease in the hydraulic conductivity of burned soils compared to unburned samples was found.

Conclusions: The obtained results lead us to assume that the post-fire erosion responses were mainly caused by the reduced cohesion and hydraulic conductivity of the burned topsoil layer, as well as by the loss of vegetation cover and the deposition of fire residues. Bearing in mind the lack of information about the effects of fire on the physical-hydro-mechanical properties of pyroclastic soils, this study represents a starting point to provide input data to post-fire slope stability analyses with the purpose of understanding the initiation mechanism of post-fire rainfall-induced soil mobilization phenomena.

P5.16

RECONSTRUCTING LANDSLIDE HISTORY IN TEPHRA-MANTLED HILLSLOPES: AN EXAMINATION OF LINKS BETWEEN SEISMOTECTONIC ACTIVITY AND LANDSLIDE FREQUENCY

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Purpose: In volcanic regions, fallout tephra deposits prone to earthquake-induced landslides widely cover hillslopes and have the potential for devastating hazards. However, the history of erosive events and current landslide susceptibility of tephra-mantled slopes remains unclear due to the lack of landslide evidence associated with paleoseismicity. Therefore, this study aims to reconstruct a detailed history of tephra deposit landslides by examining the distribution of landslides induced by the 2016 Mw 7.0 Kumamoto earthquake and possibly by prior large earthquakes on the Takanoobane lava dome (TLD) in the Aso caldera region, southwestern Japan.

Methods: We performed geomorphological interpretations using airborne light detection and ranging (LiDAR) data acquired before and after the 2016 seismic event and stratigraphic investigations of tephra deposits in the TLD. First, we identified landslides that existed before the event. We also mapped coseismic landslides on aerial photographs taken just after the event. Stratigraphic investigations were conducted at the following three sites on the TLD: outcrops of the head scarp of the largest coseismic landslide (K1), two borehole cores extracted from the center of an older landslide(O1) and from the top of the lava dome. Ten tephra samples and five humic soil samples were collected for tephrochronology and radiocarbon dating. Finally, we surveyed existing articles that referred to landslides and paleoearthquakes around the study area to compile age distributions of possible geomorphic events.

Results: We identified five landslides (K1-K5) induced by the 2016 seismic event and 12 older landslides (O1-O12) wholly covered by vegetation. Scars of recent coseismic landslides ranged from 1,050 to 14,920 m2; those of older landslides were estimated to be 1,110-15,730 m2. The K1 landslide occurred on the southwest-facing slope, where older landslides were not recognized before the earthquake. Its slip surface was formed at the base of the 30 ka pumice layer. The largest one of the older landslides (O1) is located on the south-facing slope, adjacent to the K1 landslide. Stratigraphic investigations revealed that most of the tephra sequence, including the 30 ka pumice layer, has already been eroded within the O1 landslide scar. Radiocarbon dating further constrained the landslide age to 7.0 ka. Because its topographic and stratigraphic features are similar to those of the K1 landslide, the O1 landslide may have been triggered by a palaeoearthquake. Miyabuchi et al. (2003) previously found a landslide deposits composed of tephra near the TLD slope and estimated its age to be 2.2 ka. Meanwhile, recent trench surveys along the source fault of the 2016 Mw 7.0 Kumamoto earthquake identified three palaeofaulting events (at 2.2-1.5, 4.3-2.9, and 6.0-4.4 ka) during the Holocene period (Ishimura et al., 2022).

Conclusions: Our investigation results and previous studies indicate that tephra deposit landslides have repeatedly occurred on the TLD slopes. However, the landslide ages do not show a straightforward relationship to the palaeoearthquake occurrences. The links between landslide frequency and seismotectonic activity should be carefully discussed based on new findings from trench surveys and other off-fault palaeoseismological studies.

P5.17
ESTIMATION OF SEISMIC PARAMETERS OF HISTORICAL EARTHQUAKES BASED ON A BACK-ANALYSIS OF THE GÜEVÉJAR LANDSLIDE, GRANADA (SPAIN)

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Purpose: The paper aims at estimating the size and location of two important earthquakes occurred in the Iberian Peninsula (the 1755 Lisbon and 1884 Arenas del Rey earthquakes) based on a landslide triggered by such earthquakes at the location of Güevéjar, Granada (Spain).

Methods: Estimation of the earthquake parameters of 1755 Lisbon and 1884 Arenas del Rey earthquakes is based on a back-analysis done on the Güevéjar landslide, using advance numerical modelling and the failure surface location obtained from a geophysical investigation conducted in the area. The critical seismic acceleration needed to trigger an instability at area under study is computed, and from that value, both the magnitude and epicentral location of an earthquake capable of inducing such landslide are estimated using empirical equations.

Results: The results lead to estimate the magnitude of the 1755 Lisbon earthquake near 8.5 (located as more than 580 km from the landslide) and the magnitude of the 1884 Arenas del Rey earthquake, in approximately 6.5 (located about 55 km of Güevéjar), being the "Ventas de Zafarraya" Fault the seismogenic source of the last event.

Conclusions: Although the landslide under study appears to be stable under present-day conditions, this stability is scarce, as the analyses conducted indicate that a reactivation of the landslide may happens if a small earthquake of a magnitude about 4.7 occurs in the surroundings of Güevéjar.

P5.18

A STUDY ON PREVENTIVE MEASURES FOR EARTHQUAKE-INDUCED LANDSLIDES IN REPUBLIC OF KOREA

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Purpose: Due to the earthquake in Turkey, the importance of preventing earthquake damage has increased worldwide. South Korea is not safe from earthquakes, either. In 2016, a Gyeongju earthquake with a record-high magnitude (ML 5.8) occurred, and in 2017, the Pohang earthquake (ML 5.4) occurred. In addition, in Korea, over the last 10 years(13-22 yr), earthquakes of magnitude 3.0 or higher have averaged an annual average Since it has occurred about 12 times, it is necessary to prepare for damage prevention. The purpose of this study is to explain the measures to prevent landslides caused by earthquakes in Korea.

Methods: Since there are no cases of earthquake-induced landslides in Korea, the evaluation methodology review and evaluation factors were derived by analyzing overseas studies. In addition, the applicability of the landslide hazard map on the national scale of Korea was examined. The earthquake-induced landslide hazard map was also established on a pilot basis based on the fault zone and epicenter of Pohang using seismic attenuation. Finally, an experimental study was conducted for critical rainfall adjustment for early warning after the earthquake. Three soil samples were collected from the cut-slope area in mountains and a direct shear test was performed to calculate the strength parameters according to the change in the water content ratio. In addition, the ring shear test according to the change in the water content ratio and the change in shear strength due to water supply during the shear was analyzed.

Results: The methodology for assessing the risk of landslides caused by earthquakes was the most common with statistical models at 59% and physical models at 23%. The factors frequently used in the statistical model were altitude, distance from the fault, gradient, slope aspect, country rock, and topographic curvature. Since Korea's landslide hazard map reflects topography, geology, and forest floor conditions, it has been shown that it is reasonable to evaluate the risk of earthquake-induced landslides using it. As a result of evaluating the risk of landslides based on the fault zone and epicenter in the Pohang area, the risk grade was changed to reflect the impact of the earthquake. As a result of the direct shear test, the cohesion decreased linearly as it approached the saturation state. When water was supplied during the ring shear test, the maximum shear strength decreased by 65.7-74.8% and the residual shear strength decreased by 53.5-60%.

Conclusions: The risk map based on the fault zone is effective when used in the selection of a target site for preventive erosion control work to prevent damage from earthquake-induced landslides. In addition, the risk map based on the epicenter can be used for efficient follow-up management in order to prioritize damage prevention measures, such as to investigate the current status of landslide damage after an earthquake, or to restore the damaged area. Also, it was estimated that after the earthquake, landslides were more likely to occur due to rainfall.

P5.19
REGIONAL SCALE LANDSLIDE ACTIVITY INTENSIFICATION INFERRED FROM SATELLITE SAR INTERFEROMETRY AFTER TRIGGERING EVENTS AND PREPARATION OF FOLLOWING LANDSLIDE SCENARIO

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Purpose: Post-seismic ground effects can induce prolonged erosion and perturbations, especially by the interaction between rainfall or climate features and the proneness of the slopes to fail. In particular, the increase in soil moisture level due to rainfalls prepare the subsequent triggering of landslides by seismic events and/or further weather storms. In this study we analyze the landslide reactivations after the August 16th, 2018, Mw 5.1 Montecilfone (Molise, Italy) earthquake and a slope instability scenario triggered by severe weather events, such as the Buran event of February 2018 in Central Italy. We infer causal relationships of landslide preparatory and triggering events (which in principle could be represented by both earthquakes and heavy rains) at basin-scale, highlighting the effect of preparatory factors in promoting the re-activations of slope instability phenomena.

Methods: Multitemporal analyses of satellite Synthetic Aperture Radar interferometry (InSAR) over the years across the triggering events have been carried out, using C-band Sentinel-1 data. The Differential SAR Interferometry (DInSAR) technique, that concerns the analysis of single interferograms, allowed to detect impulsive phenomena such as landslide reactivations and nonlinear movements such as the acceleration of a landslide. Therefore, the "unperturbed" conditions before the triggering event, have been compared with the post-event conditions and with the available landslide inventories, in order to perform a quantitative analysis on the landslide activity variations at a basin scale. The Advanced interferometric techniques allowed the analysis of time series of displacement at large scale and therefore the detection of any trend change in the deformation pattern of the landslides. This analysis at basin scale can reveal the spatial distribution of landslides reactivations following a triggering event.

Results: A sharp increase in the number of landslides characterizes the year following the earthquake of Montecilfone under equal rainfall conditions: in particular, considering the number of landslide reactivations, a positive percentage variation equal to +118% was determined for the post-seismic year with respect to the 1st pre-seismic (2017–2018) year. The intensification of landslide activity after a low-magnitude earthquake, involved the first year after the earthquake, and the most significant increase in landslide number, occurred in the 3 months immediately following the earthquake. This suggests that the seismic event contributed to reducing the resistance of the soils and acted as a preparatory factor for the rainfall-induced reactivations. Moreover, the detection of the acceleration trends of deformation over time reflects the destabilizing action of a triggering event such as exceptional weather events.

Conclusions: InSAR analyses provide large-scale data that allow regional landslide reactivation scenarios reconstructions, involving a different kind of multi-temporal approaches, exploiting A-DInSAR or DInSAR techniques. This study concerned landslide instability scenarios that have been affected by triggering events (both seismic events and weather storms) which have acted as a crucial destabilizing factor on the slopes, for a prolonged time period and Therefore, it allowed to infer causal relationships between preparatory factors and triggering events.

P5.20

RISK ASSESSMENT AND PREDICTION OF DEBRIS FLOW DISASTER IN BAILONG RIVER BASIN, CHINA

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Purpose: Debris flow risk comprehensively reflects the natural and social properties of debris flow disasters and is composed of the risk of the disaster-causing body and the vulnerability of the carrier. The Bailong River Basin (BRB) is a typical mountainous environment where regional debris flow disasters occur frequently, seriously threatening the lives of residents, infrastructure, and regional ecological security. In the context of global warming, the frequency and intensity of debris flow disasters in BRB are increasing, causing more and more harm. It has become a prominent problem in current disaster prevention and reduction, and it is urgent to study the risk prediction of debris flow disasters in the future.

Methods: Field surveys, machine learning algorithm, ground movement monitoring, contribution weighted addition and future land use simulation were involved in this study.

Results: By considering a complete catchment, based on remote sensing and GIS methods, we selected 19 influencing factors such as area, average slope, lithology, NDVI, average annual precipitation, landslide density, river density, fault density, etc. and applied machine learning algorithm to establish a hazard assessment model. The analysis showed that the Extra Trees model is the most effective for debris flow hazard assessments, with an accuracy rate of 88%. Based on socio-economic data and debris flow disaster survey data, we established a vulnerability assessment model by applying the contribution weighted addition method. We used the product of debris flow hazard and vulnerability to construct a debris flow risk assessment model. We used CMIP6 climate model set simulation data to calculate the future debris flow disaster hazard of BRB under three scenarios (SSP1-2.6, SSP2-4.5 and SSP5-8.5), and calculated the vulnerability of disaster-bearing bodies in different periods of the BRB combined with social and economic data. On this basis, the change of debris flow disaster risk in the BRB during 2020-2100 is predicted to provide scientific support for disaster prevention and mitigation and climate change adaptation in the basin. The catchments at a very high-risk were distributed mainly in the urban area of Wudu District and the northern part of Tanchang County, that is, areas with relatively dense economic activities and a high disaster frequency. Under SSP1-2.6 and SSP2-4.5 scenarios, debris flow disaster risk showed a decreasing trend during 2040-2100. On the contrary, under SSP5-8.5 scenario, debris flow risk showed a significant increase trend. Compared with 2020, the ranges of high and extremely high risk levels of debris flow disaster under SSP1-2.6 and SSP2-4.5 are reduced, and the risk of debris flow tends to decrease. Under SSP5-8.5, the high and extremely high risk ranges increase significantly, and the risk of debris flow tends to increase

Conclusions: These findings indicate that the assessment results provide scientific support for planning measures to prevent or reduce debris flow hazards. The proposed assessment methods can also be used to provide relevant guidance for a regional risk assessment of debris flows in the BRB and other regions.

P5.21

USING MULTI-TEMPORAL AIRBORNE LIDAR DIGITAL ELEVATION MODEL FOR THE POST-LANDSLIDE EVOLUTION OF A DEEP-SEATED LANDSLIDE

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Numerous deep-seated landslides were triggered by the extreme heavy rainfall of 2009 Typhoon Morakot in southern Taiwan island. Among these landslides, Erwanping deep-seated landslide with area of 130 hectares, a rotational slide, destroyed several railway sections and downslope of Erwanping station of Alishan Forest Railway. The damage interrupted the railways and roads and threaten the stability of Erwanping station, a cultural heritage of mountain railway since 1912. Therefore, the comprehensive investigation and monitoring are still in progress for remediation and management after 2009 Typhoon Morakot. This study presents the failure mechanism and post-landslide topographic evolution of Erwanping deep-seated landslide by micro-structure interpretation, geological exploration and geotechnical monitoring to understand the stability of mountain railway and station.

Study area consists of the thick colluvium on the detrital sedimentary rocks of Miocene Nanchuang Formation. According to the attitude of strata, N46-48°E/22°N, study area locates in dip slope area. The bedrock of landslide can be divided to two layers using the results of the geological survey and cores interpretation. The upper and lower layers are a shale with thin sandstone occasionally and a thick sandstone, which of 5m and 15m in thickness, respectively. The colluvium of 10m to 43m in thickness is divided to ancient and recent layers based on cores interpretation.

Five periods (2007, 2011, 2013, 2016, 2019) of 1m high-resolution airborne LiDAR digital elevation model and four periods (1980, 2008, 2009, 2019) of aerial orthoimages are adopted for topographic evolution analysis. The elevation differences of two periods LiDAR show the variations of surface, which relates to the erosion and deposition of slope failures. Erwanping deep-seated landslide was triggered by the heavy rainfall of 2009 Typhoon Morakot and the maximum elevation difference can up to 60m. The topographic features such as scarp, gully and fissure, are delineated by 1m high-resolution slope map. Therefore, slope failure features of post-landslide evolution can be identified by inter-period elevation differences, changes of multi-temporal aerial orthoimages and in-situ survey.

The monitoring system includes inclinometers and groundwater level gauges, those were installed based on the results of geological investigation. Hydrogeological features as surface runoff and groundwater level change are surveyed and monitored after heavy rainfall event. The shear behavior at critical slip zone of 37m-40m in depth were detected since the groundwater rise about 10m after heavy rainfall. The traces of surface runoff become gullies and infiltrate into cracks. It shows that the water flows of surface and underground caused the topographic change of post-landslide.

According to the integrating investigation and monitoring results, Erwanping deep-seated landslide separated to twelve slope failures as two main failure mechanisms. (I) 6 shallow debris slides from secondary scarp surface to fan and (II) 6 deep-seated rock slope deformations at the upslope. Besides, diagrammatic sketches of twelve slope failures showing the evolution with the morphological variation between 2007 and 2019. Moreover, the longitudinal geological profile shows the ancient and recent colluviums, and subsequent deposits. In summary, post-landslide evolution and instability area can be identified by multi-temporal LiDAR digital elevation model.

P5.22

FIELD EXPERIMENT ON THE SPATIAL - TEMPORAL EVOLUTION OF SOIL MOISTURE OF A RAINFALL INDUCED LOESS LANDSLIDE: IMPLICATION FOR EARLY WARNING

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Purpose: The increase in moisture within the slope due to rainfall is an important mechanism for landslide formation; however, it is still unclear how rainfall-induced landslide moisture varies spatially and temporally, and what the soil wetting patterns preceding the slide. In this study, we selected the foot of a landslide deposit that has occurred in the Bailong River basin for an artificial rainfall landslide simulation experiment. While using sensors to record slope movement processes and internal moisture changes, and time-series 3D-ERT technology is used to monitor the spatio-temporal evolution of the hydrology within the slope. This enabled us to understand the movement and wetting process of the landslide induced by rainfall and identify the significance of spatio-temporal variability of hydrological evolution for early warning of rainfall-induced landslides.

Methods: On-site in-situ artificial rainfall landslide simulation experiment, Point sensor monitoring, geophysical technology (Electrical resistivity tomography) and geostatistical analysis.

Results: The movement and wetting processes of the slope exhibited spatio-temporal heterogeneity. The collapse failure at the slope foot and the generation of tension cracks in the slope indicate that the slope may develop into a regressive failure mode; the slope shows a semi-continuous movement of initiation, acceleration, deceleration to stability. The initial saturation and infiltration process (preferential flow) will significantly affect the internal moisture evolution of the slope; the adjustment of the slope structure induced by the internal seepage erosion on slopes is an important reason for the influence of the slope seepage state on the wetting process. The synergistic analysis of moisture evolution and slope movement process shows that high overall saturation on slopes may be not necessary for slope movement initiation. The information on the variability of the spatio-temporal evolution of water within the slope, represented by the mean saturation and standard deviation, which may serve as a precursor to the slippery slope movement. It was found that the saturation and standard deviation of the slope increased during the movement accelerated; during the movement decelerated, the saturation and standard deviation of the slope fluctuated without a clear trend of increase or decrease. In addition, the wetting process within the slope foot may be indicative of the movement process of the slope.

Conclusions: The spatial and temporal evolution characteristics of moisture within rainfall-induced slopes, obtained based on the 3D-ERT technique, show good agreement with the movement processes of the slopes, and the temporal evolution of the average saturation and spatial differences in moisture distribution at the slope scale may indicate further movement trends of the slopes. this study demonstrates the potential of the time-series 3D-ERT technique for the quantitative monitoring of the spatial and temporal hydrological evolution of landslides and remote tl-ERT monitoring may be as an possible early warning method for landslide monitoring.

P5.23

CAUSES OF CREEPING LANDSLIDE UNDER LONG-TERM DISTURBANCES: A CASE STUDY OF THE LIKAN HIGHWAY LANDSLIDE

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Purpose: In recent years, the number of landslide disasters caused by slope excavation has increased at home and abroad. The sequence and frequency of slope excavations affect slope stability. A comparative study on the causes of prolonged creeping landslides under multi-stage cut slopes and damaged landslides under single-stage cut slopes can improve the causal mechanism of cut slope landslides.

Methods: In this study, long time series optical remote sensing images were used to study the evolution process of the Likan Highway landslide group. The present development characteristics and causes of landslide groups were identified through field investigation. The surface deformation velocity of landslide groups was obtained based on time-series InSAR technology, and the evolution stage of landslide groups was analyzed.

Results: It is found that there is variability in the spatial deformation of the Likan Highway landslide group, and the lower part of the two landslides is deformed more severely than the upper part, and both are compliant, traction loess-mudstone interfacial landslide. Adverse geological structure is the basic condition of landslide deformation, and the changes of slope excavation, rainfall and groundwater promote the development of landslide group. The height of the cut slope is the primary reason for the deformation of the Likan Highway 1# landslide, and the concentrated erosion of water from the drainage channel is the main reason for the multiple failure of the Likan Highway 2# landslide. The area of the unstable slope on the landslide 1# and 2# of Likan highway was determined to be 1.45×105m2 and 8.88×104m2, and the volume was 2.57×106m3 and 1.14×106m3, respectively, based on the ground deformation velocity, crack length and direction of the landslide group. In addition, we also found that the lower part of both landslides are in the isokinetic deformation stage, and the upper part is converting from deceleration deformation to isokinetic deformation.

Conclusions: Deformation characteristics of the Likan Highway landslide is variable in both temporal and spatial dimensions. In the time dimension, the initial excavation of the slope of the Likan Highway from 2002 to 2005 resulted in a sharp unloading of the slope. From 2005-2016, the landslide was in slow deformation. Increased landslide deformation from 2016 to present. In the spatial dimension, the upper part of the landslide is weakly deformed, and the lower part shows a bottom-up multi-stage regressive damage.

P5.24

EFFECT OF STRENGTH ATTENUATION ON FAILURE DURING SLOPE FAILURE EVOLUTION

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Purpose: Slope failure is associated with changes in pore water pressure induced by rainfall, but there are always cases where a slope is stable during heavy and continuous rainfall, and fails during light rainfall. Therefore, this paper further discusses the relationships between pore water pressure and slope failure.

Methods: This paper used the ratio of the rainfall amount that triggers a landslide to the total annual rainfall as the critical rainfall ratio. This value was obtained from in-situ rainfall simulation experiments of shallow natural slope failure, regional group-occurring landslides and individual landslides. In addition, a field rainfall simulation experiment on a natural slope was carried out in the Luoyugou watershed of Tianshui City on the northwestern Loess Plateau. There were 21 rainfall days during the 30 days of the study period.

Results: The critical rainfall ratio for slope failure is approximately 9.33–10.11 times higher under artificial rainfall than under natural rainfall. If in-situ rainfall simulation experiments assume that ratio represents the minimum rainfall required for slopes to transition from relative stability to failure, then a single heavy or continuous rainfall event appears unlikely to cause pore water pressure to be raised to a level where the shear strength of the soil in a potential sliding zone will be sufficiently reduced to trigger widespread landslides, except for extreme natural rainfall events. This is contrary to the frequency with which landslides are induced by natural rainfall events in reality. In this paper, the in-situ rainfall simulation experiment showed that failure did not always occur when the pore water pressure near the failure surface reached the maximum static pore water pressure that could be provided by rainfall. Instead, the experiment found that the high pore pressure may create conditions that allow for soil failure during subsequent rainfall periods, even if the pore pressure is then lower. In addition, failure occurred first where internal material was continuously taken out of the slope; the electrical conductivity results indicated that the soluble minerals in the soil continuously dissolve and migrate under the action of water during the period between slope stabilization and failure.

Conclusions: The initial soil strength (S) can be divided into two parts: Sp, controlled by pore water pressure, and Ss, controlled by structure. The factors that promote changes in Ss include the external environment, structural reorganization as pore water pressure increases and dissipates, and motion state. The rainfall provided by a single or continuous rainfall event will rarely be sufficient to force sufficient reductions in S to trigger a landslide. If assume that antecedent rainfall events cause discontinuity and the irreversible attenuation of Ss, creating a reduction in S before a landslide occurs, it is likely that increases in the pore water pressure driven by subsequent natural rainfall events can more easily trigger a soil landslide, even if the rising pore water pressure is not particularly high.

P5.25
GEOMORPHOLOGICAL FEATURES, EVOLUTION PROCESS AND HAZARD OF POTENTIAL LANDSLIDES IN COMPLEX MOUNTAIOUS LANDSCAPES

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Purpose: Landslide inventory is critical tool to grasp the spatial distribution of landslide, decipher triggers and failure mechanism and assess risk. Potential landslides are likely to occur in the near future, which need more attention. Synthetic Aperture Radar Interferometry (InSAR) can effectively detect ground deformations over large regions and provide crucial pre-failure information for potential landslide recognition. This helps to further identify and determine the location and evolution stage of potential landslides, and finally map a regional potential landslide inventory. We explore the geomorphological and geological controls of potential landslides in the Bailong River basin (BLRB) based on DEM and geomorphometric analysis. Meanwhile, hazard of potential landslides is assessed by analyzing the activity and geomorphology. This work provides vital foundation for geohazard risks mitigation and management in study area.

Methods: Interferometric Point Target Analysis, identification of the potential landslides based on Google Earth imagery and deformation rate map, field survey and UAV observation, geology and topography analysis, a new matrix for evaluating hazard of the potential landslides

Results: We mapped 217 potential landslides in the BLRB. The potential landslides are classified into earth slide (ES), loess slide (LS), earth flow (EF), debris slide (DS), loess flow (LF), complex landslide (CL) and rock fall (RF). The dominant landslide type is ES and the characteristics of other landslides are more distinctive. The potential landslides tend to cluster spatially in soft lithologic and fault zones. The proportion of landslide area in middle Devonian (D2), middle and upper Silurian (S2+3) exceeds 30%. And 59% of landslides are distributed within 1 km of the fault, indicating that the potential landslides in BLRB are affected by faults. The kernel density maps show that all potential landslides tend to cluster along rivers. In addition, LSs, EFs, LFs and CLs present different cluster characteristic. We established a matrix for hazard assessment based on deformation features and geomorphological features. The potential landslides are classified into four levels: low, moderate, high and very high. The result shows that 24% of potential landslides exceeds high level. Two potential landslides are in very high level, which need more attention.

Conclusions: Multi-source remote sensing technology and geomorphological investigation can be applied to potential landslide identification in complex mountainous areas. We constructed first detailed potential landslide inventory and deepened understanding of landslide development in the BLRB. Soft lithology and fault control the spatial distribution of potential landslide in the BLRB. The established matrix combining evolution processes and deformation features can used for hazard assessment of potential landslide. This research contributes to assess risk and early warning of the potential landslides in the BRLB.

P5.26
CLIMATE CRISIS AND INFLUENCE ON SNOWFALL IN THE ITALIAN PHYSICAL TERRITORY IN THE LAST THIRTY YEARS - CLINO1991-2020

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The behavior of snowfall has become one of the most important indicators for understanding the evolution of the current climate crisis, particularly, in areas characterized by a temperate climate of mid-latitudes, in its different types. However, in order to correctly define a signal from a scientific point of view, homogeneous data without large time gaps are needed (WMO, 2015). All this in a Mediterranean basin, characterized - in the industrial zone, by a temperature increase higher than that calculated globally - 1.26 Vs. 1.12°C - (IPCC, 2021), compared to the pre-industrial period and identified as an important thermal hot spot of future climate simulation models. (Tuel et al, 2020). In Italy, studies related to recent nivology are scarce (e.g. Fazzini et al, 2005; Fazzini, 2007) or limited at mesoscale mountain environment. The only homogeneous nivometric survey network extended to the entire Italian territory belongs to the Air Force Meteorological Service (SMAM) resulting from the 24-hour controlled monitoring meteorological stations at the airport and the Air Force Meteorology Offices (UMA). The 38 time series, analyzed for the period 1991-2020 are located throughout the country; the largest country is located in the plains and hills, only 7 of them are located at mountain altitudes (elevation above 700 m.asl). For each of them, the main snow parameters were analyzed - daily and seasonal fresh snow height, number of days with snowfall > 1 cm and persistence of snow on the ground. Through the analysis of the trends of each parameter, the national picture was finally characterized. The initial results of the analysis are very interlocutory and show considerable differentiation of signals in the different climatic zones of the territory. In general, however, it would be evident that the sum of seasonal snowfall tends to decrease over the Po Valley and increase slightly in the south-central while everywhere there is evidence of a decrease in the number of days with snow on the ground - even at high altitudes . In addition, there is a tendency for the delayed onset of the snow season and ground cover to be a function of the marked increase in autumn temperatures during the same observation period. Clearly, by combining this general study with more recent or existing mesoscale studies, it will finally be possible to define the trend of snow cover in a scientifically proven manner and, through more in-depth statistical approaches, to understand the evolution of this parameter in the different climatic areas that characterize a complex territory such as Italy.

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THEME 6

PROGRESS IN LANDSLIDE SCIENCE AND APPLICATIONS

P6.1

A PRELIMINARY STUDY ON 3D ELASTIC DISLOCATION INVERSION USING HIGH DENSITY SURFACE DISPLACEMENT DATA

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As advances of the Multi-Temporal Interferometric Synthetic Radar (MT-InSAR) technology, high density of surface displacement data can be obtained. The MT-InSAR technology has been increasingly applied to long-term monitoring of slope activities of potential deep-seated landslides, Chen & Kuo (2022). It is natural to ask whether it is possible to use this surface displacement data to infer the depth of landslide failure surface for landslide hazard mitigations. Aryal et al. (2015) applied the classical dislocation theory in seismology to estimate the landslide failure surface and gained a certain degree of success. In this work, we present an extension of the elastic dislocation method to a framework for general 3D landslides.

The framework begins with a free body of a landslide mass. For demonstration purposes, a standard spherical landslide mass is presented, Figure 1. It is obtained by using the minimal smooth surface method proposed in Kuo et al. (2020). The method is based on a prescribed landslide area-volume relation and is readily available to generate 3D landslide masses with an acceptable accuracy. Then the forward elastic calculation can be performed, when dislocation field is given on the bottom failure surface. We assume that the dislocation is smooth and tangential to the failure surface and can be prescribed by means of polynomials. For example, we assume a dislocation field on the failure surface as shown in Figure 2(a), perform the forward elastic calculation for the mass, and randomly sample a certain number of the surface displacements, as shown in Figure 2(b). Let the surface displacements to mimic the displacement data measured by the InSAR, then we can inverse for the coefficients of the dislocation polynomial. Procedures for verifying grid dependence and noise immunity of the inversion have been proposed and tested, Figure 3. The result indicate the feasibility of the 3D elastic dislocation inversion and the process is to be used to assess the computational settings. Then the inversion error between the actual and inversely computed surface displacements can be calculated, and along this direction, the failure surface will be determined as the surface that generates the minimum inversion error among a collection of presumed landslide masses.

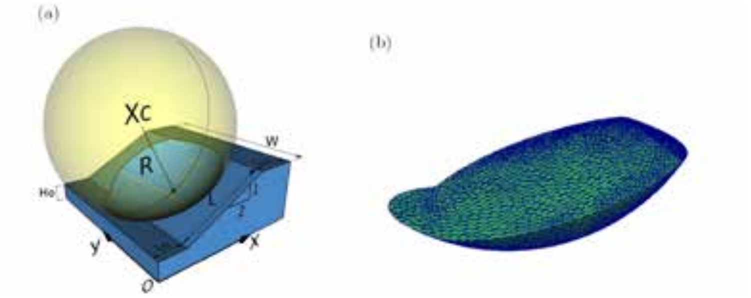


Fig. 1: a) the example landslide slope and assumed spherical failure surface, b) the landslide mass and computational mesh.

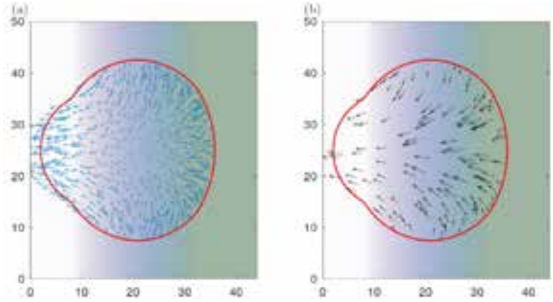
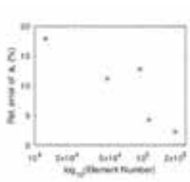


Fig. 2: a) the assumed specified dislocation displacement on the failure surface, b) the randomly sampled surface displacement incurred by the specified dislocation. Note that the lenght scales of the two subfigures are different, exaggerated, and only one fifths of data points are swown for clarity.

(a)

	Total Ele. Num.	Degree Of Freedom	$\|a^{inv} - a^{given}\|/\|a^{given}\|$
1	200,160	2,434,779	2.5%
2	114,164	1,392,084	4.3%
3	94,080	1,150,209	12.8%
4	47,140	581,751	11.2%
5	12,720	156,787	17.9%



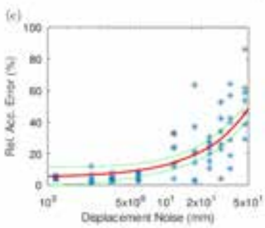


Fig. 3: a) the grid dependence of theexample inversion. Symbols a^{inv} and a^{given} stand for the inverse calculated and specified coefficients of the dislocation polynormials. b) graphic presentations of the grid dependence. c) noise immunity of the inversion. It is measured by the relative errors of the inversed coefficients of the displacement polynormilas (y) with respect to the added random noise level (x). The noise is white noise displacements whose strenght is measured by its standard deviation.

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P6.2

BASAL PORE WATER PRESSURE EVOLUTION OF RAPID FINE-GRAINED MATERIAL FLOWS

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Purpose: The speed evolution and runout length of rapid fine-grained material flows are analytically modelled by taking into account the evolution of the basal pore water pressures according to consolidation process typically affecting the involved materials, as well as their possible increments initially generated due to several phenomena (e.g. earthquakes) and during the motion, due to the slope curvature coupled to undrained and oedometric conditions.

Proposed model: The motion of a fine-grained material block of thickness h and length b (1 m length along the direction orthogonal to the slope) is considered. The slope α of the sliding surface may generally decrease/increase along its curved path (s = curvilinear abscissa, r = curvature radius). A trapezoidal initial pwp (pore water pressure) distribution (pw(z)) within a basal layer of thickness (S = percentage of saturated layer ε[0,1]) is assumed (Figure 1). The initial values pw,t0 and pw,b0 of pwp, at the top and the base of the saturated layer, depend on the values of hydrostatic interstitial pressure ( ) and on the excess pwp u(z,t) (z, normal to the sliding surface), initially due to phenomena such as consolidation, earthquakes. During the motion, excess pwp may be generated along curved paths due to centripetal force as well as, consequentially, to the increase of total normal stresses under undrained and oedometric conditions (Lambe & Whitman, 1969), expecially for fine – grained materials.

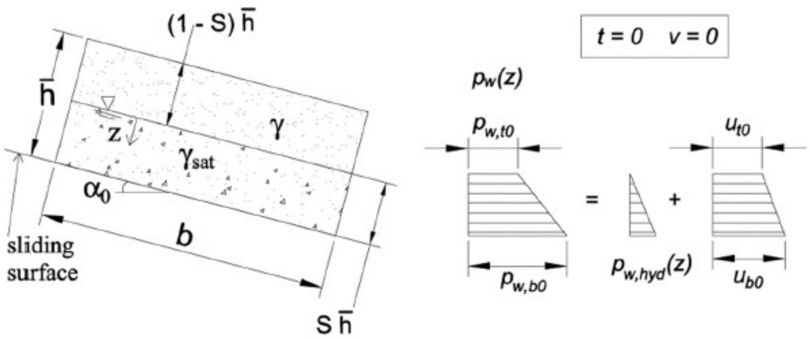

Fig. 1: Geometry of the sliding mass and assumed initial distribution of pore-water pressure.

The governing law of motion of the sliding block, representing the flowing material, is (Federico & Cesali, 2017):

$$\ddot{s} + \dot{s}^2 \left\{ \frac{1}{m(s(t))} \frac{dm}{ds} + \left[1 - \frac{((1-S)\gamma + (\gamma_{sat} + \gamma_w)S)\bar{h}b}{g\, m(s(t))} \right] \frac{tan\varphi'}{r(s)} \right\} - g\left[\sin\alpha(s) - \cos\alpha(s)\, tan\varphi'\right] - \left[p_{w,hyd}(z = S\bar{h}, t) \frac{b}{m(s(t))} \right] tan\varphi$$

φ' being the basal shear resistance angle; the mass (m) of the sliding block may vary due to erosion/deposition processes along its motion.

Results: The large scale test performed at the USGS on August 25, 2009 (Iverson et al., 2012) is analysed (Figure 2). Measurements of basal pwp at sections I, II and III (curved path, see Figure 2) are interpreted by the proposed model. The following parameters are assumed:α1 = 31°; α2 = 2.4°; L1 = 80 m; = 0.15 m; b = 30 m; γ = 18.0 kN/m³; γsat = 20.6 kN/m3; ϕ' = 39.6°; constant mass; S = 0.6.

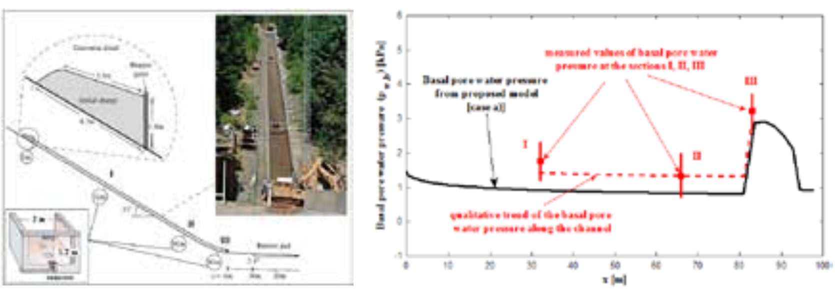

Fig. 2: Experimental apparatus and results obtained through the proposed model.

Conclusions: The evolution of pwp at the base of fine-grained materiale flow along curvilinear paths is analyzed through an analytical ("block") model. Through a reasonable choice of physical/mechanical parameters, experimental measures of basal pwp are interpreted, particularly its increment at the section from which the curvature of the slope bottom profile begins to change.

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P6.3

EXPLORING DIFFERENT NUMERICAL METHODS TO IMPROVE THE UNDERSTANDING OF SLOW-MOVING LANDSLIDES DYNAMICS IN LOWER AUSTRIA

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Purpose: Determining the mechanisms of slow-moving landslides and the critical conditions for the slow-to-fast sliding transition remains a challenge. Numerical models can be used to better understand the physical processes controlling the behaviour of rainfall-triggered landslides and to simulate their displacement under different hazard scenarios. The main objective of this research is to test and select the best fitting models to simulate landslide displacement and the hydro-mechanical coupling of a complex slow-moving landslide. This information is fundamental to develop different hazard scenarios and to estimate their potential impact. The models will be tested in the study site of Hofermühle, located in a complex transition zone between the geological units of the Flysch Zone, the Klippen Zone and the Northern Calcareous Alps in Lower Austria.

Methods: The conceptual model of the slope is developed by integrating monitoring data from various surface and subsurface parameters obtained from a long-term monitoring project at the study site. Numerical simulations will be used to characterize the mechanical response of the materials to changes in hydro-meteorological conditions. For this purpose, numerical models based on the Finite Element Method (FEM) and the Material Point Method (MPM) will be tested. The modeling process will use a cascading mudflow event triggered in 2013 as a reference. The selection of the best fitting models and the calibration process are based on the hydro-meteorological information from the long-term monitoring process, field surveys, in-situ observations, and deformation data from the inclinometers.

Results: The long-term monitoring process has provided meaningful information on the landslide dynamics of the study site. The Hofermühle study site is characterized by high spatial and temporal non-uniformity of deformation. There are several indications of non-linear deformation responses to hydro-meteorological changes on the hydrologic system considered during the modeling process. In fact, heavy rainfall events and snowmelt appear to alter the stress state of the slopes, resulting in delayed acceleration pulses. Although it has experienced a steady creep over many years, there are indications of potential cascading hazards that could be triggered within the landslide bodies.

Conclusions: Lower Austria is a region highly susceptible to the occurrence of slow-moving landslides, and therefore, integrating different modelling techniques to understand their failure mechanisms and dynamics provides a valuable opportunity to assess potential impacts, in order to improve preparedness of the region. Several modeling approaches are planning to be evaluated on the basis of their performance and the monitoring data. Exploring and integrating different numerical methods is a useful approach to better understand landslide triggering factors and mechanisms in complex environments. Long-term, continuous monitoring of slow-moving landslides provides a valuable opportunity to obtain detailed, multi-temporal information that feeds the modelling process and helps to understand the complex failure mechanisms and dynamics of these phenomena. Numerical models are useful tools to study progressive failure, and determine critical combinations of groundwater levels, soil water content, and precipitation rates that could contribute to the determination of different hazard scenarios, such as accelerations or cascading hazards occurring within the landslide body.

P6.4

THE ROCK-TOWER FAILURE MECHANISM OF THE MT. CATIELLO ROCK AVALANCHE (AMALFI PENINUNSULA, SOUTHERN ITALY)

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The January 3, 2002, rock avalanche of Mt. Catiello (Positano, Amalfi Peninsula, Italy) is a type of rock slope collapse unusual in southern Italy for what regards volume of rock material involved and mechanisms, because resembling typical slope failures occurring across the Alpine chain. This landslide was studied to understand the peculiar failure mechanisms, which were preliminary appraised by deformation patterns observed on a still-looming minor rock block, adjoining to the collapsed one.

The study was carried out by the reconstruction of a detailed 3D slope model elaborated by UAV photogrammetry which allowed the detailed recognition and characterization of discontinuities sets and stratigraphic settings of the carbonate series as well as the reconstruction of an engineering geological model of the rock slope based on the Rock Mass Rating (RMR) and Geological Strength Index (GSI) characterizations. In addition, the evolution of the stress state generated in the rock mass in the pre-failure conditions were estimated by the RS2 (Rocscience, Inc.) finite element numerical code which allowed the estimation of the Strength Reduction Factor (SRF) for four different slope engineering geological models accounting for different combinations of structural settings of the rock-mass. To complete the analysis, the mobilized and deposited rock volumes were calculated by a comparison between topographic settings preceding and following the landslide event.

As principal results obtained, the unstable rock slope was recognized as formed by two superimposed engineering geological units with different mechanical behaviours. The upper one comprises a calcareous-dolomitic stratigraphic interval with a thick bedding, while the lower one is formed by a medium thinned alternation of dolomitic limestones and marls. Both units are characterized by a downslope dip direction and a low angle of dip. Moreover, by the comparison of pre- and post-landslides topographic settings, a tower shape of the rock block collapsed was recognized involving the upper engineering geological unit and separated from the behind slope by a principal and sub-vertical open crack corresponding to a fault plane. The volume of the rock-tower collapsed was estimated of about 88.000 m3. The landslide mechanisms were related to the occurrence of both a rock-tower which was proved, by the stress state modeling, as determining an enhanced stress state at the base of the rock-tower causing its progressive sliding over the bedding planes of the lower unit until the collapse, which likely occurred by a toppling mechanism.

The subvertical fracture, the accommodation of the deformations within the ductile calcareous-dolomitic stratigraphic interval of the series in which the tensile stresses are propagated, and the mechanical stress in the rock mass, have led to a progressively stepped fracturing and to the gradual slip and collapse of the rock-tower. This failure mechanism was already recognized as determining large rock-slope collapses in the Alpine chain (Martin et al, 2020).

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P6.5

INTEGRATED APPROACH FOR THE INVESTIGATION OF SLOW KINEMATIC LANDSLIDES: THE VICARI CASE STUDY (SOUTHERN ITALY)

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Purpose: The study is focused on the analyses of two large landslides (Figure 1A) involving the NW and SW slopes of Vicari (Sicily, Italy), a village on the right central bank of the catchment of one of the most important rivers in Sicily (San Leonardo River). The reactivation of relict landslides and the triggering of new landslides occurred in 2015 between February and March because of the intense rainfall that has taken place in the first months of the year; these phenomena had a destructive impact on the structures and infrastructures (Figure 1D) , many of these built just before 2015 and have also made permanent changes to the geomorphological features of the area as lakes formed by the barrier of landslide (Figure 1B) and major changes to the topographic surface (Figure 1C).

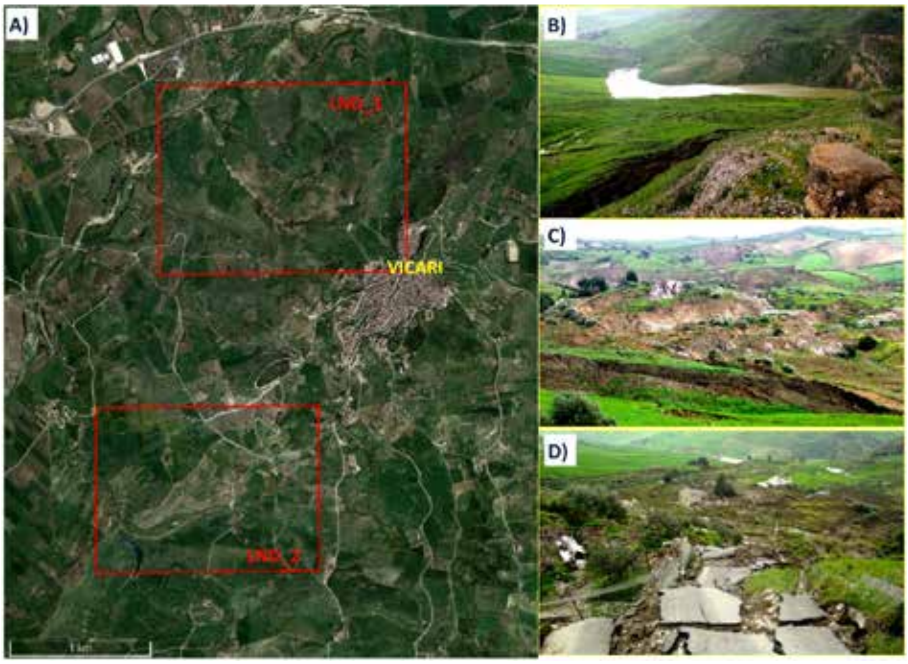

Fig. 1: Location map of the study areas (a) and some pictures showing the high impact of the landslides on the geomorphological features (b), topographic surface (c) and infrastructures located within the Vicari landslide bodies.

Methods: The analysis was conducted through the application of traditional field methods and satellite-based remote sensing techniques. Field surveys, geological and geomorphological analysis, borehole log-stratigraphies, high-resolution photo interpretation, and analysis of DTM available for the study area allowed reconstruction of the geometry and the characteristics of the landslides in the very large areas (2,5 sq. and 2 sq. for LNS_1 and LNS_1, respectively). For LND_2 geotechnical analyses were carried out to investigate the whole landslide activation and reactivation mechanisms also in the light of the rainfall records and the fundamental role played by the pore water pressure in the landslide triggering. Considering the wide area of the investigation, remote sensing techniques have been applied in order to reconstruct the kinematic of the landslides. Specifically, Differential SAR Interferometry (DInSAR) technique using radar images of the constellation SENTINEL-1 was carried out to evaluate the mean deformation rate and time series of displacements.

Results: For both landslides, the detected sectors show changes in the velocity of deformation and thus in mechanical behavior, well detected by SAR data and by the geological, geomorphological and geotechnical analysis. Moreover, an in-depth analysis of the kinematic and possible triggering factors has been achieved.

Conclusions: The availability of the remote sensing data proved essential for this study for both defining the geological model and for performing the site-specific analysis of landslides allowing for characterization in terms of extension and velocity of both the entire landslide areas and the associated landforms within them.

P6.6

NUMERICAL MODELLING OF A RETROGRESSIVE FAILURE IN THE SOURCE AREA OF THE MONTAGUTO LANDSLIDE

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The Montaguto landslide (southern Italy) has been periodically active since at least 1954. Recently, the most destructive period of landslide activity began in April 2006, when the landslide deposits reached the national road SS90 and damaged several farmhouses.

On November 7th, 2018, La Montagna landslide occurred at the upper-western side of the Montaguto landslide, causing a retrogressive enlargement of the source area (Guerriero et al., 2022). It is a first-time failure that moved, after a phase of accelerating creep, as a translational-compound initial slide evolving into earthflow (Guerriero et al., 2022), characterized by a length of 390 m and an estimated volume of 300,000 m3. Field observations indicate that landslide geometry and kinematic are controlled by the slope geologic structure, according to literature evolutionary models (e.g. Pinto et al. 2016). Furthermore, the upper sliding block of the La Montagna landslide moved mainly along a thin (~5-10 cm) clay layer widely cropping out along its eastern flank. Along the lower flow have been surveyed lateral strike-slip faults that materialize landslide flanks, however not fully developed as in the source area.

Based on such observations, the aim of this research is to deeply investigate the triggering processes of the La Montagna landslide by flanking field observations and surveys, and literature data analysis, a physics-based modelling in order to reproduce the failure mechanism. For this purpose, modelling was carried out on the base of: i) a slope stability back-analysis, to determine material shear strength parameters at slope failure by the software SWedge (Rocscience, V.6.0); ii) a 3D modelling based on FLAC 3D (V.7.0) considering also the role of rainfalls in landslide triggering. To this purpose, hydrological initial data was set in input according to the characteristics of the triggering rainfall event, considering that such analysis is focused on the period of maximum paroxysm of landslide that occurred between the last week of October and the first week of November 2018. The geometry of the landslide was derived by means of field survey and literature data. Obtained results are enable to reproduce the failure process of La Montagna landslide according to the wedge failure mechanism observed. Such modelling represents an important contribution to the knowledge of the La Montagna landslide and more widely, of the kinematic evolution of the Montaguto landslide.

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P6.8

MACHINE-LEARNING FOR DETECTION AND PREDICTION OF CLIFF FAILURES ON THE BALTIC SEA COAST IN MECKLENBURG–WESTERN POMERANIA (FEDERAL REPUBLIC OF GERMANY)

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Purpose: This study presents the initial findings of the project “AI-supported evaluation of mass movement potentials at cliffs of Mecklenburg-Western Pomerania”. Its primary purpose is to determine the feasibility of applying advanced machine learning (ML) mapping on high-resolution images to identify and segment features contributing to cliff failures. Also, it aims to evaluate the possibility of making informed predictions about future cliff failures based on established ML models.

Methods: Between October 2021 and November 2022, we conducted four aerial survey campaigns with a DJI Phantom 4 RTK drone equipped with a 20-megapixel optical sensor and a DJI Matrice 200 V2 equipped with a DJI XT2 thermal sensor. We covered four locations with different cliff types. The drone surveys followed the predefined flight plan to simplify the processing workflow and increase the comparability between different surveys. First, the collected data were used for the photogrammetric generation of point clouds and digital elevation models for change detection analysis. In the next step, we generated labeled datasets and utilized Convolutional Neural Networks (CNN) to perform supervised classification and segmentation tasks on color and thermal images. Therefore, we applied a transfer learning approach by fine-tuning pre-trained models.

Results: The collected imagery covers different rocks and soils composing the different cliff types under different weather conditions allowing us to differentiate the various potential failure mechanisms and their precursors, if applicable. Change detection on multi-temporal high-resolution DEMs and point clouds at the four project sites provides good results in identifying and quantifying new cliff failures. The cliff-type classification model shows already sufficient accuracy. The labeled dataset for the segmentation task includes features such as cracks, slope springs, erosional channels, cliff undercuts, vegetation, and artificial objects.

Conclusions: Using change detection results in combination with ML mapping, we anticipate being able to set up a prediction model for future coastal changes. Our preliminary results demonstrate the efficacy of transfer learning with limited amounts of custom data for the classification and segmentation task. Currently, we lack sufficient data for a prediction model. However, this situation will improve throughout the project, which is slated to end in 2024.

P6.9

DOES RANDOM FOREST OUTPERFORM THE GENERALIZED ADDITIVE MODEL? AN EVALUATION BASED ON RAINFALL-TRIGGERED LANDSLIDES IN THE STYRIAN BASIN, AUSTRIA

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Purpose: Landslides are among the most important natural hazards in the alpine area and their forelands in Austria. In the Styrian basin more than 3000 landslides occurred after heavy rainfall events in 2009 and 2014. These have threatened the local population and have caused significant damage to infrastructure. The area affected during a 2009-type event could grow by up to 45% in a 4 K global warming scenario, making appropriate and robust landslide susceptibility predictions a necessary prerequisite for decision-makers. In recent years, the emerging use of machine learning (ML) techniques promised improved predictive performances compared to conventional methods. The objective of this study is to compare random forest (RF) and generalized additive model (GAM). RF is one of the most widely used ML classification methods, while GAM is a semi-parametric statistical model that has previously been applied in this area. In both models, land surface, geology, hydrometeorological, and land use variables are linked to observed slope failures. Does RF outperform GAM, and are there other pros and cons that need to be considered?

Methods: For the comparison, we used common (post-hoc) diagnostic tools. For the performance assessment, we applied spatial k-fold cross-validation to obtain bias-reduced performance estimates. Variable importance was assessed using a post-hoc permutation-based approach for the final models. The local spatial structure of the produced maps (percentile-transformed) was evaluated using semivariograms (i.e., speckled vs. smooth maps). Throughout the study design, we used the area under the receiver operating characteristic curve (AUROC) as a performance measure, and applied a spatial tuning of the RF hyperparameters (i.e., num.trees, sample.fraction, mtry).

Results: Our results showed outstanding performances for both models, with GAM having slightly higher estimates (0.94 median AUROC for GAM and 0.93 for RF, respectively). The variable importance revealed a similar pattern for the three most important variables (five-day rainfall, slope angle, and forest type). However, there was a discrepancy in the geology predictor, which was of high importance in the GAM (ranked fourth) but not in the RF (ranked last). Regarding the local spatial structure of the maps, the RF map showed a higher spatial discrimination and was more speckled compared to the GAM map (sill 0.042 and nugget 0.01 in RF vs. sill 0.041 and nugget 0.007 in GAM, respectively), confirming findings of other studies.

Conclusions: In this study, we found no clear evidence that RF outperforms GAM. Instead, RF is accompanied by higher computational demands (due to hyperparameter tuning; around 4 minutes on a high-performance computing cluster vs. few seconds to fit a GAM), a more difficult map to communicate, and a limited ability to interpret the modelled predictor-response relationships. However, RF may be beneficial in purely predictive settings involving big, unstructured or highly correlated data.

P6.10
DEEP LEARNING-BASED LANDSLIDE OCCURRENCE TIME DETECTION USING SAR

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Motivation: Landslides are one of the major destructive geological hazards worldwide, causing thousands of fatalities and significant economic losses yearly. A comprehensive landslide inventory is essential to estimate the risk and potential damage caused by landslides. Most existing landslide inventories provide comprehensive spatial attributes but lack temporal information, i.e., landslide occurrence time. Optical and synthetic aperture radar (SAR) satellite data are increasingly used to support landslide occurrence detection due to their multi-spectral and textural characteristics, multi-temporal revisit rates, and large area coverage. Compared with optical sensors, SAR sensors are not limited by clouds and light conditions and can detect the time of landslide occurrence in near real-time. However, precise detection of landslide occurrence time is a big challenge for landslide evolution research due to time-series of SAR data disturbed by different rainfall, snowfall, vegetation, and human activities.

Methods: This study aims to compare the performance of different unsupervised methods for anomaly detection related to landslide occurrence time in time-series of SAR data. The approaches evaluated for this purpose are K-means, Isolate Forest, Autoregressive Integrated Moving Average (ARIMA), Seasonal and Trend decomposition using Loess (STL), Autoencoders, and Breakout detection and newly proposed a combination of the Long Short-Term Memory (LSTM) model and breakout detection.

Preliminary results and outlook:

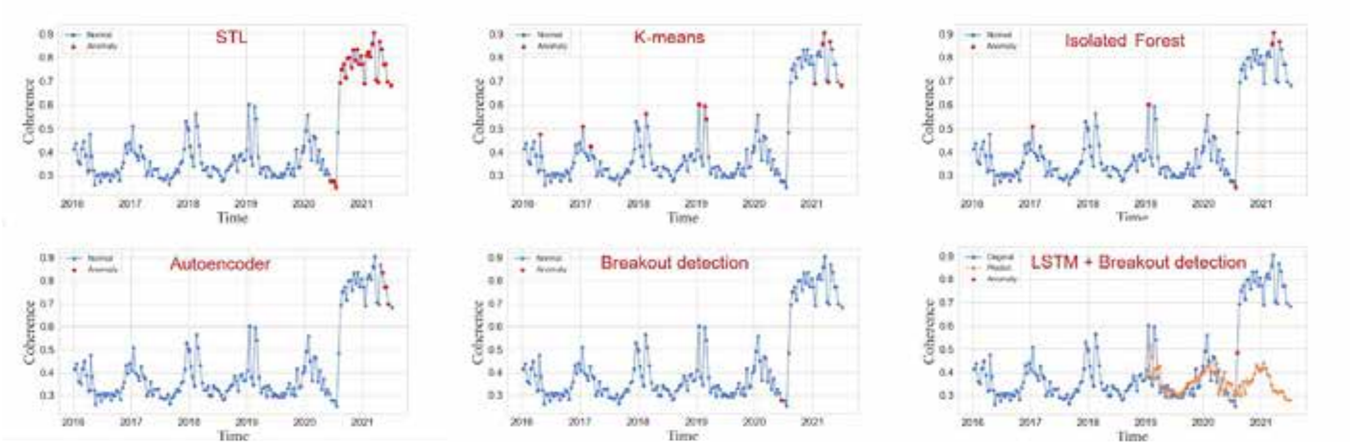

Fig. 1: Time detection results using the six methods. Red dots represent anomalies. Blue dots represent normal.

In this study, we experimented with the July 21, 2020 Shaziba landslide in China using the time-series of interferometric coherence derived from Sentinel-1 data covering the landslide body between May 1, 2016 and July 31, 2021. Figure 1 shows the time detection results based on the six methods. The commonly unsupervised methods (STL, k-means, Isolated Forest, Breakout detection, and Autoencoder) exploited for time detection always provided a lot of false positives and false negatives and could not identify the failure time correctly. The result using the improved semi-supervised method shows that the predicted and real time-series of coherence match each other very well before the failure, whereas the correlation between the two decreases dramatically after the failure. Then, the time responding to the landslide occurrence time can be accurately identified. With the above results, we found that commonly unsupervised methods cannot detect the time correctly due to noise. In contrast, the semi-supervised approach is able to identify the time accurately due to the break-detection method pre-detected part of the time-series of coherence without anomalies and used it to train the LSTM model. However, incorrect detection is inevitable once the pre-detected data used to train the model is mixed with anomaly data. In the next step, we will try the unsupervised method based on deep-learning to identify the landslide occurrence time without the pre-detected training data.

P6.11
DETECTION OF PRECURSORS TO THE TRIGGERING OF GRAVITATIONAL INSTABILITIES: MULTI-PARAMETER CHRONICLES, ARTIFICIAL INTELLIGENCE AND MODELLING

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Purpose: Landslides are governed by the combined actions of predisposing (relief, lithology, geomorphology, etc.) and triggering factors (earthquakes, meteorology). With the impacts of global change, mountain regions are experiencing increase in the level of hazard. To deal with landslide hazards, the adaptation of the prevention of natural hazards to climate change is prescribed, in particular with the definition of warning and alert systems based on multi-parameter observations and on modellings. The objectives of our work are to study the dynamics of landslides and to quantify the effect of internal and external forcings through machine learning techniques. The aim is to understand from the analysis of long data time series, which are the factors which control possible change in slope behavior over time (stable/unstable regime) and to quantify the return frequencies. Further, the objective is to work on several case studies to implement and test generic model for landslide forecast.

Methods: The daily dataset consists in observations acquired at the Séchilienne landslide (Isère, France) for period from 1992 to 2021 including succession of instability and stability phases. The temporal analysis of the data is performed through innovative techniques of exploration and quantification of multivariate correlation, based on machine learning and artificial intelligence with the use of Random Forest regression models. These models have been trained to simulate the specific slope behaviors in both high, moderate and low groundwater and rainfall conditions. The target data are displacement acquired by extensometers located on the unstable slope. The prediction data are rainfall and temperature acquired at Mont-Sec and Luitel lake weather stations, and efficient rainfall calculated with the Oudin's method. These exogeneous variables are calculated with rolling windows of 5 to 30 days to extract features (maximum value, number of rainy days, amount of cumulative rain, etc.) for each time window.

Results: The predictions obtained by applying Random Forest model on the displacement periods didn't fit very well with the real values but succeeded in preserving the trend of the displacement as well as the temporality of the peaks of displacement. The increase in the number of decision trees and the maximum depths of the trees tends to a slight improvement in the accuracy of the forecasts. The most impactful features in forecasting displacement data were those related to effective rainfall and air temperature.

Conclusions: A forecasting model brings positive results on machine learning, where the displacement trend could be globally identified. However, the model remains to be refined by exploiting in more detail the important features, as well as by adding new data from hydrogeology and soil mechanics to constrain the model. The contribution of physical data coupled with external data seems to give promising results.

P6.12

SHALLOW LANDSLIDE MULTI-TEMPORAL DIGITAL MAPPING IN NORTH-WESTERN ITALY: A MACHINE LEARNING APPROACH

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Purpose: The goal of this research is to develop a multi-temporal mapping and analysis system for shallow landslides. Machine Learning (ML) systems will be trained with multispectral satellite images to identify surface landslides. The iteration of this process on a series of multi-temporal satellite images allows to trace back to the historical period in which the landslide occurred. This system can obtain spatial and temporal quantitative information of surface landslides, not only remotely but even directly during fieldwork. Possible future developments could consider the application of this technology to a semi-automatic detection-validation-monitoring system of surface landslide events.

Methods: In the first phase, we selected open available landslide datasets (Landslide4Sense, IdroGEO, Italian regional databases). These were analyzed in detail to assess their accuracy to obtain a trained model to accurately recognize individual landslides. Two study areas were selected in north-western Italy: the mountain area of the Ligurian Alps and the hilly area of the Langhe-Monferrato. In these sectors we created a landslide dataset for the refinement of the ML model, using SENTINEL images, Google Earth Pro and QGIS. Three ML models (U-Net, Landslide4Sense, Landsifier v1.0) have been trained on the prepared datasets to select the best model for the specific purpose of this research. The trained ML system has been tested on a second landslide dataset (not included in the training dataset). Field testing has been conducted by geomorphological map surveying with proven and experimental digital mapping systems to obtain the landslide coordinates. The trained ML system extracts the geometry and the historical period in which the landslide occurred.

Results: The expected results can be summarized in four points: (i) the realization of a high-quality landslide dataset; (ii) the training of an ML model for the mapping of shallow landslides; (iii) the application of the ML system on multi-temporal datasets for (iv) the extrapolation of the temporal period in which a landslide occurred. For the first two points, a thorough analysis of existing data is necessary to build a robust ML model trained for landslide recognition. For the third and fourth points, the system implemented in this research has been tested on well-known landslides in the study areas. This approach allows a first specific quantitative evaluation of the system developed on real direct geomorphological mapping survey.

P6.13
APPLYING EXTREME GRADIENT BOOSTING MODEL FOR LANDSLIDE SUSCEPTIBILITY ASSESSMENTS

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Landslides are considered as one of the most distractive natural hazards affecting large portions of natural and man-made environment, with huge in most cases consequences in human life and properties (Ilia et al., 2015). They appear as complex natural phenomena the exact mechanism of occurrence, in time and space, an also progress and evolution are not fully understood. In recent years, Machine Learning (ML) methods have been the dominate investigation tool in landslide susceptibility assessments, when trying to model the spatial probability of occurrence without considering triggering factors, magnitude or intensity of the landslide. ML appears to perform with high precession and accuracy, whereas in most cases surpassing the performance of expert-driven and statistical based methods. In this context, the main objective of the study was to apply an ensemble method, Extreme Gradient Boosting (EGB) method, whereas Shapley Additive explanations (SHAP) method was used for evaluating the importance of each landslide related variable through Shapely values (Lundberg and Lee, 2017). To test the developed methodology, an area at the regional unit Magnesia and parts of the municipalities, Volos, Zagora-Mouresi and South Pellion was selected. Nine landslide-related variables were used, namely: elevation, slope, aspect, curvature, plan curvature, profile curvature, lithology, distance from river network, and distance from faults (Chrysafi et al., 2021). Based on the results of SHAP analysis, elevation, aspect, and lithology were among the most important variables, whereas slope, distance from river network and distance from faults followed (figure 1).

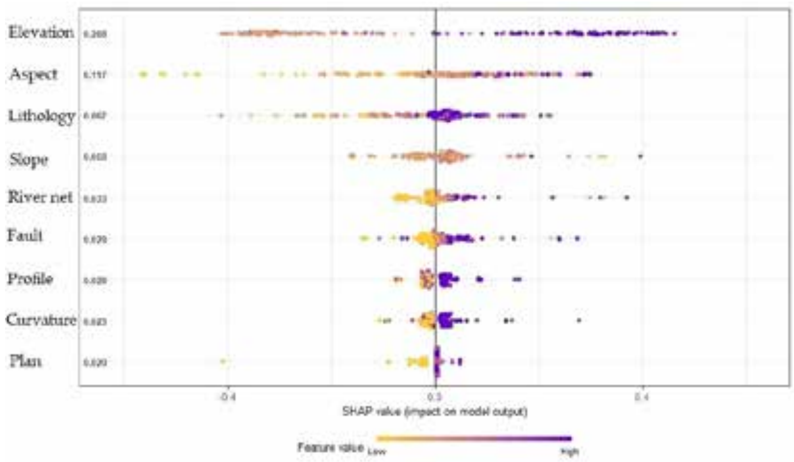

Fig. 1: Importance based on SHAP values.

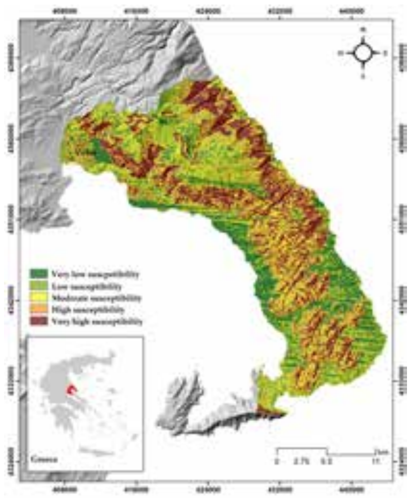

Fig. 2: Landslide Susceptibility by Extreme Gradient Boosting model.

Figure 2 illustrates the spatial distribution of the landslide susceptibility values predicted by the EGB method that has been classified to five classes, very low, low, moderate, high and very high susceptibility. Approximately, 27.50% of the total area, is classified as very high susceptibility, mainly located in areas characterized by elevation less than 800m, north, north-east slopes, covering mainly metamorphic geological formations. The accuracy of the prediction achieved by the EGB method reached 81.81%, whereas sensitivity was estimated to be 80.43% and specificity 83.34%.

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P6.14

CONSTRUCTING REAL-TIME MONITORING SYSTEM FOR ROADSIDE LANDSLIDE PRONE SLOPE THROUGH SEISMIC SPECTROGRAMS BY DEEP NEURAL NETWORK

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Purpose: Irregular occurrence of landslides on its prone slope poses significant risks to the road user. Traditionally, monitoring landslide occurrence for a target slope is based on some attached sensors on fence structures reaching the two dimensions warning function; however, some rocks may bounce out of fences, and that equipment is complicated to install on steep slopes. Recent advanced seismic monitoring techniques offer full 3D monitoring purposes and are easy to install; thus, we would like to build a real-time monitoring system based on seismic signals analysis.

Methods: We addressed seismic analysis on the two high-risk slopes in Taiwan. One location is the slope with frequent post-failure landslides, named Daman landslide; the other is multiple boulders distributed on the upslope with high rockfall risk, called the Kukuan slope. Both slopes contained two seismic stations deployed at different elevations with real-time data transmission functions. When a landslide occurs, the ground vibration caused by material propagation is recorded by seismic stations. Then, their spectrograms' features can reflect the physical process of landslides. The high-elevation station documented the signals earlier than the low-elevation station due to being near the initial stage of the mass moment process. To keep the features from two stations, we vertically contacted two spectrograms as one image. As the growing number of landslides, two-station spectrograms have been inputted into Deep Neural Network (DNN) to make robust perdition models.

Results: Three different sizes of datasets, ten thousand, forty thousand, and a hundred thousand two-station spectrograms, were applied in the DNN. The result found that using the pre-train model with loading initial weighting from VGG16, the model result reached higher accuracy than without initial weighting of VGG16 architecture. However, the difference was gradually decreased by enlarging the dataset. The bigger dataset as well as got higher accuracy. For a dataset of a hundred thousand images, the model accuracy was higher than the pre-train model with initial weighting. That reached 0.98 in two target slopes for effectively identifying post-failure landslides and rockfall.

Conclusions: By real-time signals function the warning system has been online with the DNN model to warn road users about landslides immediately.

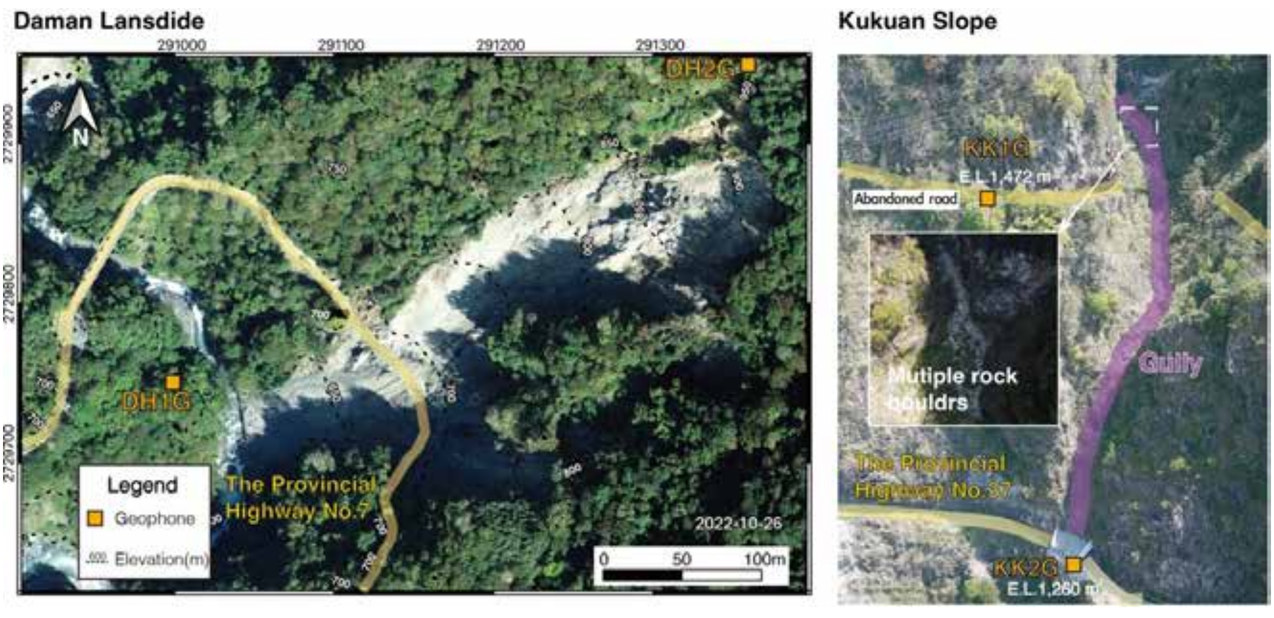

Fig.: Research area with seismic station distribution.

P6.15
A COUPLED HYDROLOGICAL AND HYDRODYNAMIC MODELLING APPROACH FOR ESTIMATING THE RAINFALL THRESHOLDS OF DEBRIS FLOWS OCCURRENCE

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Purpose: Rainfall-induced hydrological processes and surface water flow hydrodynamics may play a key role in initiating runoff-generated debris flows. In this study, a new framework based on an integrated hydrological and hydrodynamic model is proposed to estimate the rainfall thresholds of runoff-generated debris flows.

Methods: In this new framework, intensity-duration-frequency (IDF) analysis is carried out to generate design rainfall to drive the integrated model to calculate grid-based hydrodynamic indices (i.e. unit-width discharge). The hydrodynamic indices are subsequently compared with hydrodynamic thresholds to indicate the occurrence of debris flows and derive rainfall thresholds through introduction of a zone threshold.

Results: The capability of the new framework in predicting the occurrence of debris flows is verified and confirmed by application to a small catchment in Zhejiang Province, China, where observed hydrological data are available.

Conclusions: Compared with the traditional statistical Intensity-Duration (ID) thresholds, the key advantage of this physically-based approach is that it can effectively take into account the hydrological processes controlled by meteorological conditions and topographic properties, making it more applicable to the ungauged catchments where historical data on debris flow occurrence is lacking.

P6.16
HYDROLOGICAL CHARACTERISTICS TRIGGERING A LANDSLIDE IN A NATURAL FORESTED HEADWATER IN TAIWAN

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Landslide occurrences are related to hydrological, geomorphic, pedological, geological, and vegetation factors, in which the hydrological response or dynamics are primary factors in rainfall-induced landslides. Experiments usually elucidate the relationships between landslide occurrences and hydrological characteristics with artificial water supplies on artificial flumes or natural slopes. However, these experiments were under specific and controlled conditions and did not necessarily address the features or mechanisms of landslides on natural forested hillslopes. This study presented hydrological dynamics recorded during a typhoon-induced landslide in a steep natural forested headwater catchment in Taiwan. This study also analyzed the topographic features and hydrogeological characteristics at the site before the landslide to explore the main factors relating to the landslide. A typhoon on August 6, 2015, brought a high rainfall amount of 370.0 mm, which caused subsurface displacements at several locations at the site. Another typhoon on September 19, 2016, also brought high rainfall amount of 271.4 mm, which caused the landslide at the downslope of the site. Compared to the two typhoon events, it was interesting that the record-high rainfall only caused the subsurface displacements but did not trigger the landslide. The dominant factors triggering the landslide were the record-high pore water pressure at the soil–bedrock interface, antecedent wet conditions, heterogeneous distribution of subsurface saturation, and the influence of previous subsurface displacements. The previous subsurface displacements not only weakened the strength of the geological structure but also enlarged the amount of perennial saturation, all of which reduced slope stability and facilitated the landslide. The landslide area could not be detected by the topographic features, although the landslide occurred at locations with shallow soil layers. Based on the dataset of electrical resistivity tomography examined before the landslide, the landslide area contained permanent saturation at the soil–bedrock interface and groundwater in the bedrock layers. In addition to vertical rainfall infiltration, the lateral subsurface water dynamics would significantly affect landslide occurrences. At least two sources of saturation feature the subsurface hydrological characteristics of a headwater. Stability analysis models or disaster warning systems should separately consider different origins of subsurface saturation and their generation processes.

P6.17

ESTIMATION OF LANDSLIDE AQUIFER PERMEABILITY CHANGES USING WATER LEVEL RESPONSE TO ATMOSPHERIC LOADING

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Purpose: The aquifer's hydrogeological properties are controlling factors to the landslides' seepage flow which would affect the stability of landslides significantly. Traditional methods such as aquifer tests for estimating hydrogeological properties are generally expensive, time consuming and unrealistic for long-term monitoring. Where water level fluctuations in response to atmospheric loading is a potential tool to measure the hydrogeological properties of landslides.

Methods: In our study, the landslide-induced permeability changes of Kualiangzi landslide were estimated by the response of water level to atmospheric loading, and the slug test was applied as well to verify the estimation method.

Results: The results showed that the Kualiangzi landslide accelerated between 20 July 2019 to 15 August 2019 according the displacement data. Before and after the landslide, the vertical pneumatic diffusivity of the unsaturated zone estimated by the water level response method is 69.12 m2/d and 276.48 m2/d respectively, vertical hydraulic diffusivity of the aquifer is 0.518×10^{3} m2/d and 1.123×10^{3} m2/d respectively, and the hydraulic conductivity of the aquifer is 2.072×10-3 m/d and 4.492×10-3 m/d, respectively. It is identified permeability in unsaturated zone increased by a factor of four and in aquifer doubled.

Conclusions: We deduce that the aquifer permeability increased following a landslide because the structure of the primary rock formation is deformed. It caused material to become looser, less dense, and more porous, resulting the aquifer permeability enhanced. Considering the costs and convenience of the water level response method, this method is a good choice for detecting the permeability changes in the landslide zone. Especially continuous measurements of the response of water level to atmospheric loading by monitoring well system is suitable to obtain temporal and spatial variation of landslide permeability. This analysis represents helpful information to better understand the relationship between landslides and groundwater.

P6.18

STABILITY ANALYSIS OF THE 2019 BRUMADINHO DAM FAILURE

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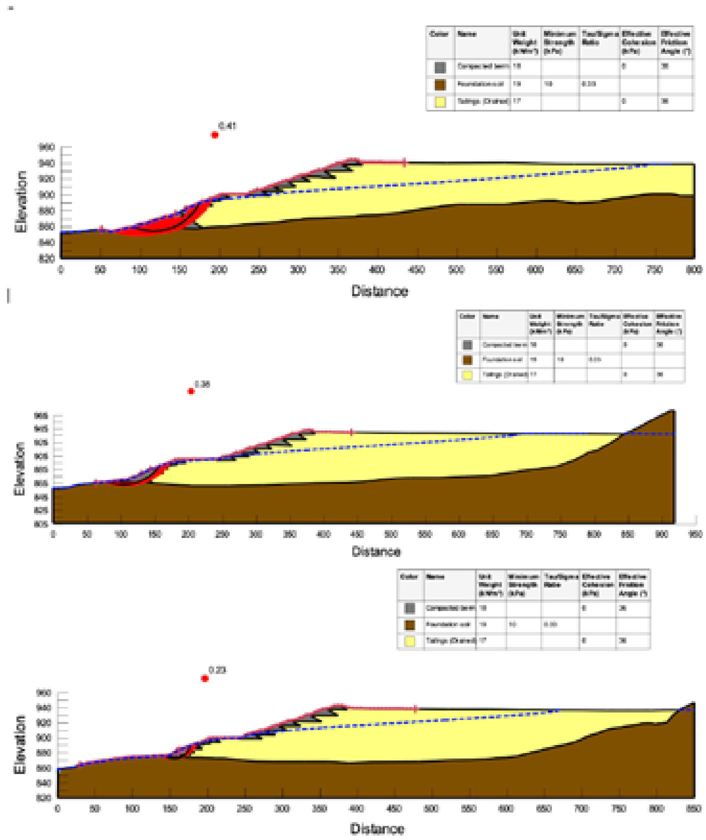
Purpose: The failure of tailings dam B-I at the Córrego do Feijão Iron Ore Mine in Brumadinho, Minas Gerais, Brazil has been the subject of high scrutiny and intense forensic investigations due to its sudden development, which resulted in a catastrophic and deadly mudflow that traveled rapidly downstream. Although theories for the dam's breach have been developed attributing this disaster to the triggering of static liquefaction based on advanced geotechnical numerical modeling, these stability assessments do not include a systematic implementation of limit equilibrium analyses (LEAs), which can help to methodically discern any inherent characteristics of the dam that may have adversely affected its overall stability. Accordingly, this study focuses of on effective stress LEAs performed on Dam B-I cross-sections to consider the scenario of slow progressive failure under drained conditions and identify any issues produced by slope geometry, without the masking effects of potential strain-softening in the materials comprising the slope.

Methods: A series of LEA analyses of the Dam B-I failure were carried out in this study. Sequential analyses were conducted to model the staged construction of Dam B-I. Dam geometry, topography, slimes boundary, and tailings layering for each construction stage were established based on LiDAR surveys, CPTu data, water table measurements. The first stage was modeled using drained strength and stiffness parameters. Each tailings lift was initially placed using elastic parameters, then the pore pressures were updated to reflect the water level. For these long-term effective stress stability analyses, the peak friction angle (measured in triaxial tests were used. These values were the same as the critical friction angles of the loose specimens, but on average 2o higher than the critical friction angle of the dense specimens due to dilatancy. Critical state friction angles of 34o, 34o, and 33o were respectively used for calculating the effective strengths of fine, coarse and the average tailings, respectively, throughout the stability analyses.

Results: By considering the ultimate water seepage regime and material strength properties reported by the forensic panel, the factors of safety obtained in this study range from a low of 0.23 to a high of 0.41 as shown below. These suggest that Dam B-I was inherently unstable, even if drained strength of the tailings (typically higher than undrained strength) were to have been mobilized.



Conclusions: The results of our study indicated that Dam B-I was marginally stable prior to the 2019 failure. The inherent instability of Dam B-I was predominantly due to its steep downstream slope which produced high shear stress ratios within the tailings. The January 2019 collapse was instigated by the loss of the reinforcing effect of matric suction following several intense rainfalls. The analyses presented in this paper show that the dam failed due to the high shear stresses exceeding the drained strength of tailings, rather than the undrained failure hypothesized by the investigation Panel. Similar FS were obtained from the limit equilibrium and finite element analyses based on the SSR method.

P6.19

CASE STUDY ON THE IMPACT OF VEGETATION ON A LANDSLIDE INITIATION UNDER TORRENTIAL STORMS

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In the framework of the nature-based solutions, vegetation has long been used in geotechnical engineering to protect slopes from surface instability phenomena. However, its effects remain difficult to quantify, given the diversity of plants in situ and the uncertainties linked to their main morphological, mechanical and physiological characteristics. Moreover, it is a common misestimation to consider roots as a mere mechanical reinforcement of the soil. This might make sense in the case of artificial reinforcement with fibres, but as plants are living organisms capable of transpiring, their impact on soil hydraulic states and matric suction should not be neglected.

In order to propose an easily applicable numerical modelling strategy, the case of a landslide that occurred on a steep slope following torrential rains in Costa Rica was analysed. After the geotechnical characterisation of the soils affected by the movement, the plant species present on the slope were identified, and their main morpho-mechanical characteristics were estimated or measured. These characteristics were used to evaluate the changes in the hydromechanical parameters of the soil due to the presence of the roots, as well as to evaluate the transpiration generated by the plants themselves. A “continuum material” approach was hence adopted to simulate the vegetated soil numerically. In addition, a failure criterion for partially saturated soils, dependent on soil matric suction and degree of saturation, was adopted in the model to better represent the soil shear strength loss upon wetting.

Using available meteorological data, the evolution of the hydraulic state of the slope in the weeks before and during the storm that caused the landslide was simulated. For comparison, the same simulation was carried out on the same slope as it was without vegetation. In addition, the evolution of the factor of safety has been calculated in correspondence with the different hydraulic states of the slope until the instability condition was reached.

The results of the simulations show that, due to transpiration, at the beginning of the storm, the slope with vegetation had a lower degree of saturation and higher matric suction than the slope without vegetation, which translates into a greater soil shear strength, which is furtherly increased by the tensile strength of the roots themselves. Due to this difference in the initial hydraulic state, the slope with vegetation reached instability a few hours later than the slope without vegetation, despite an increase in soil water permeability due to root penetration/growth in the medium. The simulated time evolution and the kinematic of the vegetated landslide were in good agreement with local observations.

This study demonstrated the importance of considering both hydraulic and mechanical effects of roots in the soil, as the matric suction induced by plant transpiration plays a key role, together with the tensile strength of roots, in delaying slope instability during heavy rainfall. In this way, more attention should be on monitoring such kind of variables within slopes, to get an accurate point of the actual factor of safety and the probabilities of landslide activation.

P6.20

BIOCLASTESIS AS TRIGGERING FACTOR FOR ROCKFALLS AND ROCKSLIDES

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Purpose: The effect of roots as triggering factors for rockfalls and rockslides is often neglected, since rock are considered so resistant that they cannot be seriously damaged by roots. However, roots can create severe problems to rocks amasses and contribute to open rock factures or fissures. These could be widened both for leverage effect and also for chemical degradation of rock. These effects may be severe, particularly for Mediterranean areas, where the dry climate forces the roots to go deep into the rock masses to find water and nourishments. Such consequences are facilitated whereas weak rocks as sandstones and calcarenites exist. Here an interesting and quite impressive case history is presented. It is a potential rockslide of several cubic meters in the Park of the Rupestrian Churches of Matera, that is part of the UNESCO World Heritage. The purpose is to give evidence of how bioclastesis can severely damage rupestrian environments and cause potential rockslide.

Methods: The impressive potential rockslide in the Park of the Rupestrian Churches of Matera, was studied using an in situ survey and a terrestrial 3D laser scanner survey. These allowed for better reconstructing the rock fracturing in that area and understanding the reason of the quite sudden opening of a fracture potentially inducing a rockfall. The survey was extend to the surrounding area to recognize the presence of other similar situations some of which completely evolved.

Results: The survey permitted to recognize that the fracture of the potential rockslide was unexpectedly due to bioclastesis phenomena, related to the presence of the roots of a fig tree. These roots widened a preexisting fracture that opened for leverage effects as well as for chemical alteration of the rock. The fracture opened more than 6 cm, while it was not possible to evaluated its depth and the continuity of the fracture, see figure 1.

Conclusions: The investigated case study allowed for evidencing the real risk of rockfall and rockslide induces by bioclastesis phenomena induced by roots of a fig tree, in calcareous sandstone of a Mediterranean area.

Fig. 1: Image of the frature, on the left side; detail of the point cloud of the fracture on the right side.

P6.21

EFFECT OF CHRYSOPOGON ZIZANIOIDES GROWTH ON HILL SLOPE STABILITY

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Purpose: Rainfall-induced landslides are dominant natural disasters in tropical and subtropical regions. These regions consist of slopes mostly vegetated with higher slope angles which remain stable throughout the dry spell. The onset of the monsoon witnessed slope failures for decades in these regions, causing loss of lives and properties. It is understood that an increase in soil saturation due to rainwater infiltration leading to a decrease in suction (negative pore pressure) which contribute to the reduction in soil shear strength, is the primary cause of these slides. The studies prove that vegetation improves soil shear and hydrological properties. To understand the mechanism of these slides, the contribution of vegetation to the hydraulic and mechanical properties of soil is significant. The effect of vegetation growth on soil hydraulic properties and the type of vegetation present are all factors to be considered in the analysis of slopes. However, seldom are studies done on this aspect. An understanding of the contribution of vegetation to the stability of slope over time and determination of soil hydraulic and strength parameter over the vegetation growth will aid in realistic slope stability analysis and improves the efficiency of early warning systems (EWS).

Methods: The present study focuses on evaluating the contribution of vegetation to the hydraulic properties of soil during plant growth. The vetiver grass (Chrysopogon zizanioides) was grown in natural conditions, and the moisture variations within the slope during the growth period were measured using moisture sensors. The plants were grown in field slopes 1400 mm * 1000 mm. The moisture content at 30 depths in the field slope was analysed. Artificial rainfall events were applied on the slope with and without vegetation, and continuous moisture changes were measured. The daily moisture readings for 45 days after achieving sufficient root growth suggested lower moisture retention in vegetated slopes. A numerical slope stability study with experimental data was conducted.

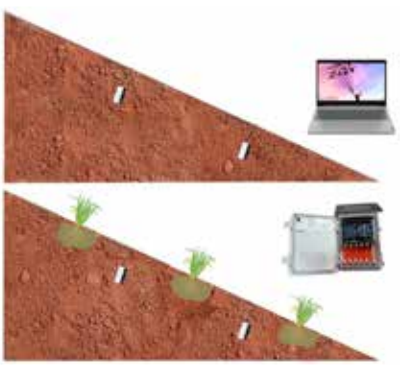

Fig. 1: Field slopes with instrumentation.

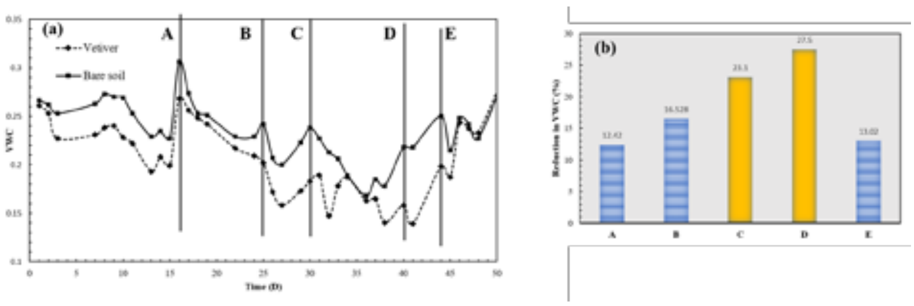

Fig. 2: Temporal variation of soil moisture of study slope.

Conclusions: The daily moisture readings for 45 days after achieving sufficient root growth suggested lower moisture retention in vegetated slopes. Also, the vegetated slope allowed less water percolation to the soil during an artificial rainfall event. The measured water contents were used to conduct slope stability of the slopes. The safety factor of vegetated slopes was much higher than the bare slope in the study period.

P6.22

VOLCANIC DEBRIS AVALANCHE PROPAGATION MECHANISMS AND DYNAMICS: FIELD EVIDENCE AND ANALOGUE EXPERIMENTS

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Purpose: Volcanic debris avalanches (VDAs) are large landslide events characterised by long runouts and high mobility. They initially propagate as slides and usually evolve into flows. Their long runouts and destructive potential pose a great hazard to communities close to volcanoes. Although many theories have been proposed to explain their runout, the mechanisms enabling it remain unresolved and poorly constrained. This is partly due to the difficulty of theoretical models to interpret and represent field observations. In this study, findings from field studies combined with analogue experiments provide insights into VDA propagation mechanisms and dynamics.

Methods: Two VDA deposits in the Canary Islands with distinct characteristics are examined: Tenteniguada (Gran Canaria), and Abona (Tenerife). The field study examines their internal structure, facies distribution and sedimentology. 3D models of outcrops and sample windows were generated using structure-from-motion photogrammetry to quantify sedimentological properties. Evaluating these data allows the generation of conceptual models for their propagation dynamics.

Results: Tenteniguada is principally composed of competent lava lithologies, which did not disaggregate, preventing the evolution to a granular mass. Rather, fractured clasts remained coherent with stresses accommodated at block boundaries. Disaggregation is low, with widespread preservation of the original structure, although displaced by brittle deformation. The deposit represents propagation by normal fault-accommodated spreading, resulting in a deposit that bears resemblance to non-volcanic blockslide deposits. The avalanche did not fully transition from a slide to a flow. In contrast, the majority of the Abona VDA deposit is composed of weak pyroclastic lithologies. It exhibits high disaggregation, microfracturing and cataclasis constituting the material granular. The low competence of the material enabled the mass to evolve into an agitated flow where the stresses were chaotically distributed in ephemeral energy chains constituting temporary shear networks throughout the mass. Lithological units are interbedded and stretched giving the deposit a form similar to the mixing of viscous fluids. The study of Abona supports the theory that VDAs can behave as granular flows with interacting particles exchanging and dissipating energy. The two volcanic debris avalanches have propagated with different rheology and dynamics and produced different deposits, owing to material properties. In addition to field evidence, small-scale granular flow analogue experiments are employed to evaluate particle interactions and energy exchange processes. Experiments show that hypotheses associating high mobility with a basal layer of fine particles are unlikely at the scale of VDAs.

Conclusions: The findings suggest that VDA mobility does not require auxiliary friction-reducing mechanisms. It is suggested that purely gravity-driven avalanches can evolve into flows due to increasing momentum and kinetic energy from their initial potential energy. However, other mechanisms can also enable long runouts according to material properties. The study highlights the effectiveness of coupling field examinations and physical experiments in understanding VDA dynamics. The clast-size analysis methodology proposed facilitates sedimentological study of indurated deposits allowing evaluation of a larger number of events, the dynamics that generated them and the hazards they pose.

P6.23

THE CASE STUDY OF THE BIG LANDSLIDE OF POMARICO (BASILICATA, SOUTHERN ITALY)

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Purpose: On the 29th January 2019, a big landslide destroyed the north east side of the town of Pomarico, South Italy. The landslide activated even if there was a large bulkhead to protect the side of the town against possible failures. The bulkhead collapsed together with the main road of the urban center as well as of the upstream buildings, seriously damaging several other buildings. Such severe landslide was unexpected, therefore purpose of this study is to investigate the causes of the landslide and the reason of the collapse of engineering structure. This is intended to get further knowledge to be able to prevent these kinds of phenomena and to design more reliable engineering work.

Methods: Several surveys were made to understand the characteristics of the landslide and its triggering factors. Geological and geomorphological investigations, with litho-stratigraphic reconstruction from boreholes, supplied the detailed landslide characterization, geophysical surveys provided important information related to 2D subsurface profiles organization and GB-InSAR monitoring were carried out to measures the displacements of post-landslide phase. It was also developed and hydrological analysis of the rainfall preceding the landslide and a critical analysis of the failure mechanism.

Results: The geological and geomorphological setting of the site and the morphological characteristics of the landslide are presented. Geophysical and stratigraphic data, contributed to the detailed characterization of the unstable slope. The results of the investigations related to the interpretation of the complex failure mechanism and the reasons of the bulkhead failure, as well as an analysis of the singularity of the triggering factors are defined.

Conclusions: This work presents the complex landslide occurred in Pomarico and focuses on the results of a multidisciplinary approach based on different investigation techniques. The integration of direct and indirect multiple surveys contributed to detail geomorphological characterization of the unstable slope. Moreover, the critical analysis of the failure mechanism allowed for obtaining information about the landslide evolution and behaviour. The study highlighted that the instability conditions were influenced by the prolonged seasonal rainfalls identifiable as the main triggering factor of the landslide. In addition, some issues of the design of the retaining engineering work were identified. Finally, special structural interventions are recommended to prevent possible new retrogressive evolutions of the landslide.

P6.24
FABRE CONSORTIUM ACTIVITY ON LANDSLIDE RISK FOR BRIDGES ACCORDING TO THE ITALIAN GUIDELINES FOR THE RISK EVALUATION AND THE MANAGEMENT FOR BRIDGES

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Purpose: The Italian Ministry of Infrastructure, after the tragic failure of "Morandi" Bridge in Genoa in 2018 issued a guideline for the evaluation and the management of the risk for road bridges. These guidelines are mandatory for road managements and motorway concessionaires; the guidelines, based on a multi-level approach, include assessments inherent to different types of risk for bridges, namely structural, seismic, hydraulic, and landslide risk. The activities required by the guidelines involve, as an initial step, a summary assessment of the attention classes for each risk listed before but performed on all the bridges and viaducts. This activity is very time consuming for the concessionaires both for the preliminary census activities and for the inspections that allow the assignment of a global class of attention for each infrastructure. In this context, the FABRE consortium was born in 2020, involving more than 20 Italian Universities, with the ambition of supporting highway concessionaires in the activities made mandatory by the entry into force of the guidelines. Inside FABRE consortium a panel of geotechnical engineers and engineering geologists was constituted to deepen the application of the guidelines to landslide risk. The group developed the first experience on practical application of guidelines to landslide risk, and worked on preparing instructions to improve the applicability of guidelines and suggesting amendments for the future releases of guidelines.

Methods: The groups from different Universities supported the Italian motorway concessionaires on the analysis of different bridges, potentially susceptible to landslide. To this aim, a preliminary analysis was done, according to guidelines, on geological maps, landslide database, literature information, in situ survey and preliminary evaluation of interaction of recognized or potential landslides with the bridge. The group shared information to create a common format for the preliminary reports on landslide risk and a uniform application of the guideline in different geological environments.

Results: Early results are quite interesting; the experience of the group is an introduction for engineers and geologists on the analysis of the interaction between bridges and landslides, and on the results of the developed experiences for a standardized application of the guidelines. In addition, the group started working in developing standardized procedure for the accurate evaluation of the landslide risk for bridges, which is the final purpose of the guidelines.

Conclusions: FABRE group for the deepening of the procedures for the evaluation of landslide risk for bridges, is actively working on this subject with interesting and immediately usable results.

P6.25

THE MONTAGUTO EARTH FLOW: REVIEW OF THE ACHIEVEMENTS IN THE LAST 16-YEAR PERIOD (2006-2022) AND INSIGHTS FOR PREDICTING FUTURE ACTIVITIES

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Purpose: This paper presents a review of the achievements obtained in the last 16 years at the Montaguto earth flow in order to obtain insights for predicting future activity. The landslide is located in southern Italy along the northern side of the Cervaro River valley, is one of the largest active earth flows in Europe. It is about 3 km long and affects an area of about 67 ha. The earth flow has a history of periodic activity, characterized by rapid surges alternating with longer periods of quiescence. In 2006, the earth flow remobilized and damaged several farmhouses and destroyed a segment of the national railway in March 2010. Mitigation measures were put in place in April 2010, consisting of deep and surficial drainage and a retaining wall at the toe.

Methods: The slope is complex, made up of Miocene and Pliocene flysch formations. The geological complexity of the slope is influenced by the presence of clayey deposits in the fold cores and pervasive discontinuities. Evolution, retrogression, movement direction, and flow segmentation of the landslide are controlled by the geological structures and lithological variation in the successions. Therefore, detailed geological model are constructed in order to identify areas of likely earth-flow enlargement and predict the seasonal behavior of earth-flow movement direction.

Results: On November 7th, 2018, a new reactivation occurred as a retrogression at the upper-western side of the source area of the Montaguto earthflow involving an estimated volume of 300,000 m3. The landslide is characterised by an upper translational block that evolves into a flow downslope. The landslide movement occurs along a well-defined clay layer with a thickness ranging between 10 and 25 cm, and is bounded laterally by strike-slip/oblique faults. The displacement history recorded by monitoring instrumentations at the upper translational landslide block during this period showed a typical hyperbolic displacement distribution and associated parabolic variation of velocity, indicating nonlinear progressive slope failure characterizing landslides involving structurally complex formations.

Conclusions: Finally, studies carried out during the last 16-year period provide a basis for interpreting the behaviour of geologically and structurally complex slopes subject to intermittent and slow-moving landslides, including factors controlling movements, and their potential sudden failure. We conclude that geological structures strongly influence earth-flow movement, which can be used to predict the behaviour of earth flows in specific areas.

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P6.26
REMOTE SENSING MONITORING OF EARTH-FLOWS: INSIGHTS AND LESSONS LEARNED FROM THE PIETRAFITTA CASE STUDY (SOUTHERN ITALY)

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Purpose: Earth flows are complex processes which are usually generated in hilly areas [1,2], often characterized by a heterogeneous displacement pattern in terms of scale, velocities, style, and directions [3-4]. When these gravitational events are affected by heavy and prolonged precipitations can assume rapid evolutions, representing serious hazards for human settlements [5]. Currently, their monitoring still represents a relevant challenge in the field of engineering geology. In literature, only few works combined and critically evaluated different remote sensing techniques specifically focused on earth flows over the same time period.

Methods: Through the assessment of data simultaneously collected at Pietrafitta earth flow (Southern Italy) by Robotic Total Station (RTS), Terrestrial Synthetic Aperture Radar Interferometry (TInSAR), Terrestrial Laser Scanner (TLS) and from satellite-based Digital Image Correlation (DIC) analysis, this work aims to show and critically evaluate the capabilities and limitations of the various remote sensing monitoring techniques.

Results: Despite DIC analysis failed to fully detect the magnitude of the displacements occurred, the comparison between sensors showed that, although differences in spatial and temporal resolutions exist, the detected deformation trends seem approximately coherent.

Conclusions: However, the results suggest that just an integrated approach based on multi-sensor data can solve limitations of each different technique when monitoring activities faced complex events such as earth flows.

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P6.27

THE PECULIAR CASE STUDY OF PIETRACAMELA, ITALY, A VILLAGE SIMULTANEOUSLY AFFECTED BY ROCKFALLS AND DEEP SEATED PHENOMENA

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Purpose: Landslides represent a major problem in human activities, especially in proximity of cities or infrastructures. These phenomena are usually classified in relation to their forming material and type of failure. It is therefore clear that during the definition of landslide risk, it is important to understand the geology of the area and the type of the expected failure. In this paper we present the peculiar case of Pietracamela, Italy. Pietracamela is a small village sited in the Central Apennines, few kilometers on the north of the Gran Sasso Mountain. The village is simultaneously affected by two different types of landslide phenomena. The SW part of the village, representing the historical part of the town, has been affected by large rockfalls, generated from the steep slope located on the South of the village. The NE part of the town represent the most recent urbanized area and has unfortunately been developed on a deep seated landslide which in the last decades has damaged buildings and infrastructures. In this context, in this research we show how the integration of different remote sensing techniques and stability analysis methods can be important in the study of complex landslide phenomena.

Methods: The rockfall area has been surveyed through the use of a Unmanned Aerial Vehicle (UAV) that allowed the definition of main joint sets and potential rockfall volume. The deep seated landslide has been studied analysing ca 20 years of InSAR data, which highlighted the rate of displacement during these years. Through the use of UAV and InSAR data and available borehole data, rockfall simulations and finite elements analyses have been performed in the rockfall area and deep seated landslide, respectively.

Results: Two main joint sets characterize the slope overhanging the SW part of the village, resulting in potential planar and wedge rock failures. The volume of rock failures vary from few to tens of cubic meters volume. The rockfall simulations highlight the possibility that future rockfall could reach the village. Finite element analysis pointed out several failure surface characterizing the deep seated movement, in agreement with existing inclinometer and InSAR data.

Conclusions: Pietracamela is simultaneously affected by rockfalls and deep seated phenomena. Rockfalls can have large volumes and can reach the SW portion of the village, highlighting the need of most suitable mitigation measures. The landslide in the NE part of the village is characterized by relatively shallow and deep seated failure surfaces. Shallow failure surfaces can be located at a depth varying from 10 to 30 meters at the contact between shallow deposit and the clayey geological formation of "Argille a Orbulina". The deep seated surfaces have been inferred at more than one hundred meters of depth, within the marls of the "Marne con Cerrogna Formation", and their influence on the slope instability have been simulated.

P6.28
COLLECTION AND REGIMENTATION SYSTEM FOR SURFACE AND METEORIC WATERS APPLIED DIRECTLY ON THE SLOPES, BOTH SILS AND ROCKS IN ANY PEDOCLIMATIC CONDITION

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The effects of a soil reinforcement with Perennial Herbaceous Plants with Deep and Resistant Rooting System (PHPDRRS) block erosion and positively influence the stability of the slope thanks to the properties of water insulation and transpiration: it decreases infiltration, cracking and interstitial pressure are reduced, improving the main geomechanical parameters of the soils.

This herbaceous plants reinforce the soil ad also protects the traditional surface hydraulic works such as channels and guard ditches, generally made of plastic materials, metal, concrete, and so, on from the silting.

It also allows to realize directly on the soil as is as the works action of collection and regimentation of surface and meteoric water, completely avoiding the use of materials and artifacts extraneous to the lithotype of the slope is made such as concrete and iron channels, bridles with stones plastic material and so on.
The advantages of this solution, realized by sowing seeds of PHPDRRS directly on the slopes are:
• Perfectly adapt to the subsidence of the slope avoiding infiltration,
• Avoid concentrated weights on the slope,
• Reduce infiltrations due to breakage and detachment of rigid structures are avoided, even as a result of different thermal expansion and water swellings between the various materials and the underlying lithotype,
• Highly reduce the speed of the flowing water in the grassed channels,
• The kinetic energy of the water, even in the presence of high flow speeds, is dissipated, instant per instant, by friction through the thick epigean coverage,
• The deep and very tensile resistant roots anchor these herbaceous species, in the underlying lithotype, do not add weigh to the slope, do not create concentrated weights and do not require any maintenance.

In addition: Increases in hydraulic flow, with respect to the assumed return times, can be managed and absorbed by the civil work itself. In case of overflow due to exceptional events, all the anti-erosion system act as anti-erosion hydraulic system. Further advantages are the drastic reduction (from 10 to 100 times) the energy consumption and pollution emission of this innovative technology compared to the traditional techniques. The total absence of maintenance. A positive environmental impact. A drastic reduction of construction times.

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