PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Ground-motion prediction equations 1964–2010

John Douglas

Bureau de Recherches Géologiques et Minières (BRGM)

Published jointly by brgm

Geoscience for a sustainable Earth

PEER 2011/102
APRIL 2011

Ground-motion prediction equations 1964-2010

(also published as Final Report BRGM/RP-59356-FR by BRGM)

John Douglas
Bureau de Recherches Géologiques et Minières (BRGM)

PEER Report 2011/102
Pacific Earthquake Engineering Research Center
College of Engineering
University of California, Berkeley

April 2011

Synopsis

This report summarizes all empirical ground-motion prediction equations (GMPEs), to estimate earthquake peak ground acceleration (PGA) and elastic response spectral ordinates, published between 1964 and 2010 (inclusive). This report replaces: the Imperial College London report of Douglas (2004a), which provided a summary of all GMPEs from 1964 until the end of 2003; the BRGM report of Douglas (2006), which summarized all GMPEs from 2004 to 2006 (plus some earlier models); and the report of Douglas (2008), concerning GMPEs published in 2007 and 2008 (plus some earlier models). In addition, this report lists published GMPEs derived from simulations, although details are not given since the focus here is on empirical models. Studies that only present graphs are only listed as are those nonparametric formulations that provide predictions for different combinations of distance and magnitude because these are more difficult to use for seismic hazard analysis than those which give a single formula. Equations for single earthquakes or for earthquakes of approximately the same size are excluded due to their limited usefulness. Those relations based on conversions from macroseismic intensity are only listed.

This report was compiled as part of Task 2 (Compilation of list of candidate GMPEs) of the Global Component on GMPEs coordinated by the Pacific Earthquake Engineering Research Center (PEER) for the Global Earthquake Model (GEM) and Workpackage 4 (Strong ground motion modeling) of the Seismic Hazard Harmonization in Europe (SHARE) project of the Seven Framework Programme of the European Commission (grant agreement no. 226769).

This report summarizes, in total, the characteristics of 289 empirical GMPEs for the prediction of PGA and 188 empirical models for the prediction of elastic response spectral ordinates. In addition, many dozens of simulation-based models to estimate PGA and elastic response spectral ordinates are listed but no details are given.

It should be noted that the size of this report means that it may contain some errors or omissions. No discussion of the merits, ranges of applicability or limitations of any of the relationships is included herein except those mentioned by the authors or inherent in the data used. This report is *not* a critical review of the models. The GMPEs are generally reported in the form used in the original references.

Contents

Chapter 1

Introduction

ESEE Report 01-1 'A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates (1969 to 2000)' (Douglas, 2001a) was completed and released in January 2001. A report detailing errata of this report and additional studies was released in October 2002 (Douglas, 2002). These two reports were used by Douglas (2003) as a basis for a review of previous ground-motion prediction equations (GMPEs). Following the release of these two reports, some further minor errors were found in the text and tables of the original two reports, and additional studies were found in the literature that were not included in ESEE 01-1 or the follow-on report. Also some new studies were published. Rather than produce another report listing errata and additions it was decided to produce a new report that included details on all the studies listed in the first two reports (with the corrections made) and also information on the additional studies. This report was published as a research report of Imperial College London at the beginning of 2004 (Douglas, 2004a). At the end of 2006 a BRGM report was published (Douglas, 2006) detailing studies published in 2004–2006 plus a few earlier models that had been missed in previous reports. Finally, at the end of 2008 another BRGM report was published (Douglas, 2008) containing summaries of GMPEs from 2007 and 2008 and some additional earlier models that had been recently uncovered.

Because of the large number of new GMPEs published in the past couple of years and the discovery of some additional earlier studies and various errors in the previous reports, it was decided to publish a new comprehensive report to replace the previous reports (Douglas, 2001a, 2002, 2004a, 2006, 2008) containing all previous reports plus additional material rather than publish yet another addendum to the 2004 report. It was also decided that, for completeness and due to the lack of another comprehensive and public source for this information, to include a list of GMPEs developed using other methods than regression of strong-motion data, e.g. simulation-based models (e.g. Douglas & Aochi, 2008). However, due to the complexity of briefly summarizing these models it was decided not to provide details here but only references — a public report on these models may be published later. Douglas (2007) compares predicted response spectra from many of the stochastic models listed.

This report summarizes, in total, the characteristics of 289 empirical GMPEs for the prediction of peak ground acceleration (PGA) and 188 models for the prediction of elastic response spectral ordinates. With this many ground-motion estimation equations available it is important to have criteria available for the selection of appropriate models for seismic hazard assessment in a given region — Cotton *et al.* (2006) and, more recently, Bommer *et al.* (2010) suggest selection requirements for the choice of models. For the selection of GMPEs routinely applicable to state-of-the-art hazard analyses of ground motions from shallow crustal earthquakes Bommer *et al.* (2010) summarize their criteria thus.

1. Model is derived for an inappropriate tectonic environment (such as subduction-zone earthquakes or volcanic regions).
2. Model not published in a Thomson Reuters ISI-listed peer-reviewed journal (although an exception can be made for an update to a model that did meet this criterion).
3. The dataset used to derive the model is not presented in an accessible format; the minimum requirement would be a table listing the earthquakes and their characteristics, together with the number of records from each event.
4. The model has been superseded by a more recent publication.
5. The model does not provide spectral predictions for an adequate range of response periods, chosen here to be from 0 to $2\,\mathrm{s}$.
6. The functional form lacks either non-linear magnitude dependence or magnitude-dependent decay with distance.
7. The coefficients of the model were not determined with a method that accounts for inter-event and intra-event components of variability; in other words, models must be derived using one- or two-stage maximum likelihood approaches or the random effects approach.
8. Model uses inappropriate definitions for explanatory variables, such as M_L or r_{epi}, or models site effects without consideration of $V_{s,30}$.
9. The range of applicability of the model is too small to be useful for the extrapolations generally required in PSHA: $M_{\min} > 5$, $M_{\max} < 7$, $R_{\max} < 80\,\mathrm{km}$.
10. Model constrained with insufficiently large dataset: fewer than 10 earthquakes per unit of magnitude or fewer than 100 records per $100\,\mathrm{km}$ of distance.

Similar criteria could be developed for other types of earthquakes (e.g. subduction). Application of these criteria would lead to a much reduced set of models. The aim of this report, however, is not to apply these, or any other, criteria but simply to summarize all models that have been published. Bommer *et al.* (2010) also note that: '[i]f one accepts the general approach presented in this paper, then it becomes inappropriate to develop and publish GMPEs that would subsequently be excluded from use in PSHA [probabilistic seismic hazard analysis] on the basis of not satisfying one or more of the requirements embodied in the criteria.'

Predictions of median ground motions from GMPEs show great dispersion (Douglas, 2010a,b) demonstrating the large epistemic uncertainties involved in the estimation of earthquake shaking. This uncertainty should be accounted for within seismic hazard assessments by, for example, logic trees (e.g. Bommer & Scherbaum, 2008).

1.1 Other summaries and reviews of GMPEs

A number of reviews of GMPEs have been made in the past that provide a good summary of the methods used, the results obtained and the problems associated with such relations. Trifunac & Brady (1975, 1976) provide a brief summary and comparison of published relations. McGuire (1976) lists numerous early relations. Idriss (1978) presents a comprehensive review of published attenuation relations up until 1978, including a number which are not easily available elsewhere. Hays (1980) presents a good summary of ground-motion estimation procedures up to 1980. Boore & Joyner (1982) provide a review of attenuation studies published in 1981 and they comment on empirical prediction of strong ground motion in general. Campbell (1985) contains a full survey of attenuation equations up until 1985. Joyner & Boore (1988) give an excellent analysis of ground motion prediction methodology in general, and attenuation relations in particular; Joyner & Boore (1996) update this by including more recent studies. Ambraseys & Bommer (1995) provide an overview of relations that are used for seismic design in Europe although they do not provide details about methods used. Recent reviews include those by Campbell (2003c,a) and Bozorgnia & Campbell (2004a), which provide the coefficients for a number of commonly-used equations for peak ground acceleration and spectral ordinates, and Douglas (2003). Bommer (2006) discusses some pressing problems in the field of empirical ground-motion estimation.

Summaries and reviews of published ground-motion models for the estimation of strong-motion parameters other than PGA and elastic response spectral ordinates are available[1]. For example: Bommer & Martínez-Pereira (1999), Alarcón (2007) and Bommer *et al.* (2009) review predictive equations for strong-motion duration; Tromans (2004) summarizes equations for the prediction of PGV and displacement (PGD); Bommer & Alarcón (2006) provide a more recent review of GMPEs for PGV; Hancock & Bommer (2005) discuss available equations for estimating number of effective cycles; Stafford *et al.* (2009) briefly review GMPEs for Arias intensity; and Rathje *et al.* (2004) summarize the few equations published for the prediction of frequency-content parameters (e.g. predominant frequency).

1.2 GMPEs summarised here

Equations for single earthquakes (e.g. Bozorgnia *et al.* , 1995) or for earthquakes of approximately the same size (e.g. Seed *et al.* , 1976; Sadigh *et al.* , 1978) are excluded because they lack a magnitude-scaling term and, hence, are of limited use. Also excluded are those originally developed to yield the magnitude of an earthquake (e.g. Espinosa, 1980), i.e. the regression is performed the other way round, which should not be used for the prediction of ground motion at a site. Models such as that by Olszewska (2006), who uses 'source energy logarithms' to characterize mining-induced events, have been excluded because such a characterization of event size is rare in standard seismic hazard assessments. Similarly, equations derived using data from nuclear tests, such as those reported by Hays (1980), are not included. Those based on simulated ground motions from stochastic source models (e.g Atkinson & Boore, 1990) and other types of simulations (e.g. Megawati *et al.* , 2005), those derived using the hybrid empirical technique (e.g Campbell, 2003b; Douglas *et al.* , 2006) and those relations based on intensity measurements (e.g. Battis, 1981) are listed in Chapter 6 but no details are given because the focus here is on empirical models derived from ground-motion data. Studies which provide graphs to give predictions (e.g. Schnabel & Seed, 1973) are only listed and not summarized as are those nonparametric formulations that give predictions for different combinations of distance and magnitude (e.g. Anderson, 1997), both of which are more difficult to use for seismic hazard analysis than those which report a single formula. For similar reasons, models derived using neural networks (e.g. Güllü & Erçelebi, 2007) are only listed.

GMPEs for the prediction of PGA are summarized in Chapters 2 and 3 and those for spectral ordinates are summarized in Chapters 4 and 5. The final chapter (Chapter 6) lists other ground-motion models that are not detailed in the previous chapters. All the studies that

[1]Note that a number of the models summarized in this report also provide coefficients for peak ground velocity (PGV).

present the same GMPE are mentioned at the top of the section and in the tables of general characteristics (Illustrations 1 & 2). The information contained within each section, and within tables, is the sum of information contained within each of the publications, i.e. not all the information may be from a single source. Note that GMPEs are ordered in chronological order both in the section titles and the order of the sections. Therefore, a well-known model presented in a journal article may not be listed where expected since it had previously been published in a conference proceedings or technical report. To find a given model it is recommended to examine the table of content carefully or apply a keyword search to the PDF. Some models (e.g. Abrahamson & Silva, 1997) provide GMPEs for spectral accelerations up to high frequencies (e.g. $100\,\mathrm{Hz}$) but do not explicitly state that these equations can be used for the prediction of PGA. Therefore, they are only listed in the chapters dealing with GMPEs for the prediction of spectral ordinates (Chapters 4 and 5). This should be considered when searching for a particular model.

To make it easier to understand the functional form of each GMPE the equations are given with variable names replacing actual coefficients and the derived coefficients and the standard deviation, σ, are given separately (for PGA equations). These coefficients are given only for completeness and if an equation is to be used then the original reference should be consulted. If a coefficient is assumed before the analysis is performed then the number is included directly in the formula.

Obviously all the details from each publication cannot be included in this report because of lack of space but the most important details of the methods and data used are retained. The number of records within each site and source mechanism category are given if this information was reported by the authors of the study. Sometimes these totals were found by counting the numbers in each category using the tables listing the data used and, therefore, they may be inaccurate.

This report contains details of all studies for PGA and response spectra that could be found in the literature (journals, conference proceedings, technical reports and some Ph.D. theses) although some may have been inadvertently missed[2]. Some of the studies included here have not been seen but are reported in other publications and hence the information given here may not be complete or correct. Since this report has been written in many distinct periods over a decade (2000–2010), the amount of information given for each model varies, as does the style.

In the equations unless otherwise stated, D, d, R, r, Δ or similar are distance and M or similar is magnitude and all other independent variables are stated. PGA is peak ground acceleration, PGV is peak ground velocity and PSV is relative pseudo-velocity.

In Illustrations 1 & 2 the gross characteristics of the data used and equation obtained are only given for the main equation in each study. The reader should refer to the section on a particular publication for information on other equations derived in the study.

In earlier reports the name 'attenuation relation(ships)' is used for the models reported. The current *de facto* standard is to refer to such models as 'ground-motion prediction equations' (GMPEs) and, therefore, this terminology is adopted here. However, as discussed by Boore & Atkinson (2007, Appendix A) there is some debate over the best name for these models (e.g. 'ground-motion model' or 'ground-motion estimation equations') and some people disagree with the use of the word 'prediction' in this context.

No discussion of the merits, ranges of applicability or limitations of any of the relationships is included herein except those mentioned by the authors or inherent in the data used. This report is *not* a critical review of the models. The ground-motion models are reported in the

[2]Generally GMPEs from technical reports and Ph.D. theses are only summarized if they have been cited in journal or conference articles.

form given in the original references except sometimes the equation is simplified if this can be easily done. Note that the size of this report means that it may contain some errors or omissions — the reader is encouraged to consult the original reference if a model is to be used.

Chapter 2

Summary of published GMPEs for PGA

2.1 Esteva & Rosenblueth (1964)

- Ground-motion model is:

$$a = c \exp(\alpha M) R^{-\beta}$$

where a is in $\mathrm{cm/s^2}$, $c = 2000$, $\alpha = 0.8$ and $\beta = 2$ (σ is not given).

2.2 Kanai (1966)

- Ground-motion model is:

$$\begin{aligned} a &= \frac{a_1}{\sqrt{T_G}} 10^{a_2 M - P \log_{10} R + Q} \\ P &= a_3 + a_4/R \\ Q &= a_5 + a_6/R \end{aligned}$$

where a is in $\mathrm{cm/s^2}$, $a_1 = 5$, $a_2 = 0.61$, $a_3 = 1.66$, $a_4 = 3.60$, $a_5 = 0.167$ and $a_6 = -1.83$ (σ is not given).

- T_G is the fundamental period of the site.

2.3 Milne & Davenport (1969)

- Ground-motion model is:

$$A = \frac{a_1 \mathrm{e}^{a_2 M}}{a_3 \mathrm{e}^{a_4 M} + \Delta^2}$$

where A is in percentage of g, $a_1 = 0.69$, $a_2 = 1.64$, $a_3 = 1.1$ and $a_4 = 1.10$ (σ not given).

- Use data from Esteva & Rosenblueth (1964).

2.4 Esteva (1970)

- Ground-motion model is:

$$a = c_1 e^{c_2 M} (R + c_3)^{-c_4}$$

  where a is in $\mathrm{cm/s^2}$, $c_1 = 1230$, $c_2 = 0.8$, $c_3 = 25$, $c_4 = 2$ and $\sigma = 1.02$ (in terms of natural logarithm).

- Records from soils comparable to stiff clay or compact conglomerate.

- Records from earthquakes of moderate duration.

2.5 Denham & Small (1971)

- Ground-motion model is:

$$\log Y = b_1 + b_2 M + b_3 \log R$$

  where Y is in g, $b_1 = -0.2$, $b_2 = 0.2$ and $b_3 = -1.1$ (σ not given).

- Records from near dam on recent unconsolidated lake sediments which are $\geq 50\,\mathrm{m}$ thick.

- Note need for more points and large uncertainty in b_1, b_2 and b_3.

2.6 Davenport (1972)

- Ground-motion model is:

$$A = \alpha e^{\beta m} R^{-\gamma}$$

  where A is in g, $\alpha = 0.279$, $\beta = 0.80$, $\gamma = 1.64$ and $\sigma = 0.74$ (in terms of natural logarithms).

2.7 Donovan (1973)

- Ground-motion model is:

$$y = b_1 e^{b_2 M} (R + 25)^{-b_3}$$

  where y is in gal, $b_1 = 1080$, $b_2 = 0.5$, $b_3 = 1.32$ and $\sigma = 0.71$. 25 adopted from Esteva (1970).

- 214 (32%) records from San Fernando (9/2/1971) earthquake and 53% of records with PGA less than $0.5\,\mathrm{m/s^2}$.

- Considers portions of data and finds magnitude dependence increases with increasing distance from source and more small accelerations increase magnitude dependence. Thus magnitude and distance cannot be considered independent variables.

2.8 Denham *et al.* (1973)

- Ground-motion model is:

$$\log Y_a = a_1 + a_2 M_L + b_3 \log R$$

  where Y_a is in $\mathrm{cm/s^2}$, $a_1 = 2.91$, $a_2 = 0.32$ and $a_3 = -1.45$ (σ is not given).

- Use records from Yonki station (20 records) which is on $50\,\mathrm{m}$ of recent alluvium and from Paguna station (5 records) which is on unconsolidated volcanic rock.

- Question validity of combining data at the two sites because of differences in geological foundations.

- Note large standard errors associated with coefficients preclude accurate predictions of ground motions.

- Also derive equation for Yonki station separately.

2.9 Esteva & Villaverde (1973) & Esteva (1974)

- Ground-motion model is:

$$Y_c = b_1 \mathrm{e}^{b_2 M} (R + b_4)^{-b_3}$$

  where Y_c is in $\mathrm{cm/s^2}$, $b_1 = 5600$, $b_2 = 0.8$, $b_3 = 2$, $b_4 = 40$ and $\sigma = 0.64$ (in terms of natural logarithm).

2.10 McGuire (1974) & McGuire (1977)

- Ground-motion model is:

$$E[v] = a 10^{bM} (R + 25)^{-c}$$

  where E indicates expectation, v is in gal, $a = 472$, $b = 0.278$, $c = 1.301$.

- Excludes records for which significant soil amplification established but makes no distinction between rock and soil sites.

- Focal depths between 9 and $70\,\mathrm{km}$ with most about $10\,\mathrm{km}$. Most records from earthquakes with magnitudes about 6.5 and most distances less than $50\,\mathrm{km}$. Uses records from 21 different sites.

- Notes that physical laws governing ground motion near the source are different than those governing motion at greater distances therefore excludes records with epicentral distance or distance to fault rupture smaller than one-half of estimated length of rupture.

- Examines correlation among the records but find negligible effect.

2.11 Orphal & Lahoud (1974)

- Ground-motion model is:

$$A = \lambda 10^{\alpha M} R^{\beta}$$

where A is in g, $\lambda = 6.6 \times 10^{-2}$, $\alpha = 0.40$, $\beta = -1.39$ and $\sigma = 1.99$ (this is multiplication factor).

- Use 113 records with distances between 15 to $350\,\mathrm{km}$ from San Fernando earthquake to find distance dependence, β.
- Use 27 records of Wiggins Jr. (1964) from El Centro and Ferndale areas, with magnitudes between 4.1 and 7.0 and distances between 17 and $94\,\mathrm{km}$ (assuming focal depth of $15\,\mathrm{km}$), to compute magnitude dependent terms assuming distance dependence is same as for San Fernando.

2.12 Ambraseys (1975b), Ambraseys (1975a) & Ambraseys (1978a)

- Ground-motion model is:

$$\log Y = b_1 + b_2 M_L + b_3 \log R$$

where Y is in $\mathrm{cm/s^2}$, $b_1 = 0.46$, $b_2 = 0.63$, $b_3 = -1.10$ and $\sigma = 0.32$[1]

- Ambraseys & Bommer (1995) state that uses earthquakes with maximum focal depth of $15\,\mathrm{km}$.

2.13 Trifunac & Brady (1975), Trifunac (1976) & Trifunac & Brady (1976)

- Ground-motion model is:

$$\log_{10} a_{\max} = M + \log_{10} A_0(R) - \log_{10} a_0(M, p, s, v)$$

$$\log_{10} a_0(M,p,s,v) = \begin{cases} ap + bM + c + ds + ev + fM^2 - f(M - M_{\max})^2 & \text{for } M \geq M_{\max} \\ ap + bM + c + ds + ev + fM^2 & \text{for } M_{\max} \geq M \geq M_{\min} \\ ap + bM_{\min} + c + ds + ev + fM_{\min}^2 & \text{for } M \leq M_{\min} \end{cases}$$

where $a_{\max}$ is in $\mathrm{cm/s^2}$, $\log_{10} A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of M_L, p is confidence level and v is component direction ($v = 0$ for horizontal and 1 for vertical). Coefficients are: $a = -0.898$, $b = -1.789$, $c = 6.217$, $d = 0.060$, $e = 0.331$, $f = 0.186$, $M_{\min} = 4.80$ and $M_{\max} = 7.50$ ($\log_{10} A_0(R)$ not given here due to lack of space).

- Use three site categories:

$s = 0$ Alluvium or other low velocity 'soft' deposits: 63% of records.

[1] From Ambraseys & Bommer (1995).

$s = 1$ 'Intermediate' type rock: 23% of records.

$s = 2$ Solid 'hard' basement rock: 8% of records.

- Exclude records from tall buildings.
- Do not use data from other regions because attenuation varies with geological province and magnitude determination is different in other countries.
- Records baseline and instrument corrected. Accelerations thought to be accurate between 0.07 and $25\,\mathrm{Hz}$ or between 0.125 and $25\,\mathrm{Hz}$ for San Fernando records.
- Most records (71%) from earthquakes with magnitudes between 6.0–6.9, 22% are from 5.0–5.9, 3% are from 4.0–4.9 and 3% are from 7.0–7.7 (note barely adequate data from these two magnitude ranges). 63% of data from San Fernando earthquake.
- Note that for large earthquakes, i.e. long faults, $\log_{10} A_0(R)$ would have a tendency to flatten out for small epicentral distances and for low magnitude shocks curve would probably have a large negative slope. Due to lack of data $\lesssim 20\,\mathrm{km}$ this is impossible to check.
- Note difficulty in incorporating anelastic attenuation because representative frequency content of peak amplitudes change with distance and because relative contribution of digitization noise varies with frequency and distance.
- Note that $\log_{10} A_0(R)$ may be unreliable for epicentral distances less than $10\,\mathrm{km}$ because of lack of data.
- Change of slope in $\log_{10} A_0(R)$ at $R = 75\,\mathrm{km}$ because for greater distances main contribution to strong shaking from surface waves, which are attenuated less rapidly ($\sim 1/R^{1/2}$) than near-field and intermediate-field ($\sim 1/R^{2-4}$), or far-field body waves ($\sim 1/R$).
- Note lack of data to reliably characterise $\log_{10} a_0(M, p, s, v)$ over a sufficiently broad range of their arguments. Also note high proportion of San Fernando data may bias results.
- Firstly partition data into four magnitude dependent groups: 4.0–4.9, 5.0–5.9, 6.0–6.9 and 7.0–7.9. Subdivide each group into three site condition subgroups (for $s = 0$, 1 and 2). Divide each subgroup into two component categories (for $v = 0$ and 1). Calculate $\log_{10} a_0(M, p, s, v) = M + \log_{10} A_0(R) - \log_{10} a_{\max}$ within each of the 24 parts. Arrange each set of n $\log_{10} a_0$ values into decreasing order with increasing n. Then mth data point (where m equals integer part of pn) is estimate for upper bound of $\log_{10} a_0$ for $p\%$ confidence level. Then fit results using least squares to find $a, \ldots f$.
- Check number of PGA values less than confidence level for $p = 0.1, \ldots, 0.9$ to verify adequacy of bound. Find simplifying assumptions are acceptable for derivation of approximate bounds.

2.14 Blume (1977)

- Ground-motion model is:

$$a = b_1 e^{b_2 M_L} (R + 25)^{-b_3}$$

where a is in gal, for $M_L \leq 6\frac{1}{2}$ $b_1 = 0.318 \times 29^{1.14\bar{b}}$, $b_2 = 1.03$, $b_3 = 1.14\bar{b}$ and $\sigma = 0.930$ (in terms of natural logarithm) and for $M_L > 6\frac{1}{2}$ $b_1 = 26.0 \times 29^{1.22\bar{b}}$, $b_2 = 0.432$, $b_3 = 1.22\bar{b}$ and $\sigma = 0.592$ (in terms of natural logarithm).

- Assumes all earthquakes have focal depth of $8\,\mathrm{km}$.
- Makes no distinction for site conditions in first stage where uses only earthquake records.
- Studies effects of PGA cutoff (no cutoff, 0.01, 0.02 and $0.05\,\mathrm{m/s^2}$), distance cutoff (no cutoff and $< 150\,\mathrm{km}$) and magnitude cutoff (all, $\geq 5\frac{1}{2}$, ≥ 6, $\geq 6\frac{1}{2}$, $\geq 6\frac{3}{4}$ and $\leq 6\frac{1}{2}$).
- Selects $6\frac{1}{2}$ as optimum magnitude cutoff but uses all data to derive equation for $M_L \leq 6\frac{1}{2}$ because not much difference and dispersion is slightly lower (in terms of ± 1 standard deviation have 2.53 and 2.61).
- In second stage uses only records from underground nuclear explosions, consistent with natural earthquake records, to derive site factor.
- Uses 1911 alluvium and 802 rock records and derive PGA ratio of alluvium to rock assuming their PGAs equal at $4\,\mathrm{km}$.
- Finds site impedance ρV_s, where ρ is density and V_s is shear-wave velocity under site, is best measure of site condition. Use $2000\,\mathrm{fps}$ ($600\,\mathrm{m/s}$) as shear-wave velocity of alluvium stations.
- Multiplies equation (after taking logarithms) by $\bar{b} = \frac{1}{2}\log_{10}(\rho V_s)$ and normalise to $4\,\mathrm{km}$.
- Notes may not be a good model for other regions.

2.15 Milne (1977)

- Ground-motion model is:

$$\mathrm{ACC} = a_1 \mathrm{e}^{a_2 M} R^{a_3}$$

where ACC is in g, $a_1 = 0.04$, $a_2 = 1.00$ and $a_3 = -1.4$.

2.16 Ambraseys (1978b)

- Ground-motion model is:

$$\bar{a} = a_1 \bar{R}^{a_2} \exp(a_3 \bar{M})$$

where $\bar{a}$ is in $\mathrm{cm/s^2}$, $a_1 = 1.31$, $a_2 = -0.92$ and $a_3 = 1.455$ (σ is not given).

- Uses data from former USSR, former Yugoslavia, Portugal, Italy, Iran, Greece and Pakistan.
- Peak ground accelerations have either been taken from true-to-scale accelerograms or have been supplied by local networks. Records have not been high- or low-pass filtered because it was found not to work with short records.
- Believes body-wave or local magnitude are the appropriate magnitude scales because interested in the high-frequency range of spectra, which are seen and sampled by strong-motion instruments, and most engineering structures have high natural frequencies.

- Most of the magnitudes were recalculated using P-waves of periods of not more than $1.2\,\mathrm{s}$ because it was found that the magnitude was dependent on the period of the P-waves used for its determination.
- Groups data into intervals of 0.5 magnitude units by $10\,\mathrm{km}$ in which the mean and standard deviations of the PGAs is calculated. This grouping minimises distance and magnitude-dependent effects. Notes that the number of observations is barely sufficient to allow a statistical treatment of the data and hence only test general trend. Notes that scatter is significant and decreases with increasing magnitude.

2.17 Donovan & Bornstein (1978)

- Ground-motion model is:

$$\begin{aligned} y &= b_1 \mathrm{e}^{b_2 M}(R+25)^{-b_3} \\ \text{where } b_1 &= c_1 R^{-c_2} \\ b_2 &= d_1 + d_2 \log R \\ b_3 &= e_1 + e_2 \log R \end{aligned}$$

  where y is in gal, $c_1 = 2,154,000$, $c_2 = 2.10$, $d_1 = 0.046$, $d_2 = 0.445$, $e_1 = 2.515$, $e_2 = -0.486$, for $y = 0.01\,\mathrm{g}$ $\sigma = 0.5$, for $y = 0.05\,\mathrm{g}$ $\sigma = 0.48$, for $y = 0.10\,\mathrm{g}$ $\sigma = 0.46$ and for $y = 0.15\,\mathrm{g}$ $\sigma = 0.41$ (in terms of natural logarithm).

  Use 25 because assume energy centre of Californian earthquakes to be at depth $5\,\mathrm{km}$.

- Consider two site conditions but do not model:
  1. Rock: (21 records)
  2. Stiff soil: (38 records)
- 32% of records from San Fernando (9/2/1971) but verifies that relationship is not significantly biased by this data.
- Most records within $50\,\mathrm{km}$ and most from earthquakes with magnitudes of about 6.5.
- Recognises that magnitude and distance are not independent variables.
- Find b_1, b_2 and b_3 by dividing data according to distance and computing b parameters for each set using least squares. Find a distinct trend with little scatter.

2.18 Faccioli (1978)

- Ground-motion model is:

$$y = a 10^{bM}(R+25)^{-c}$$

  where y is in gal, $a = 108.60$, $b = 0.265$, $c = 0.808$ and $\sigma = 0.236$ (in terms of logarithm to base 10).

- Records from sites underlain by cohesive or cohesionless soils with shear-wave velocities less than about $100\,\mathrm{m/s}$ and/or standard penetration resistance $N \leq 10$ in uppermost $10\,\mathrm{m}$ with layers of considerably stiffer materials either immediately below or at depths not exceeding a few tens of metres.

- Focal depths between 9 and $100\,\mathrm{km}$.
- Free-field accelerograms, to minimize soil-structure interaction.
- Excludes records with $\mathrm{PGA} < 0.4\,\mathrm{m/s^2}$.
- 21 Japanese records processed with frequency cutoffs of bandpass filter, for baseline correction, adjusted so as to account for length and mean sampling rate of records and response characteristics of SMAC-2. 4 of remaining 7 records processed in same way.

2.19 McGuire (1978)

- Ground-motion model is:

$$\ln x = b_1 + b_2 M + b_3 \ln R + b_4 Y_s$$

  where x is in $\mathrm{cm/s^2}$, $b_1 = 3.40$, $b_2 = 0.89$, $b_3 = -1.17$, $b_4 = -0.20$ and $\sigma = 0.62$.

- Uses two site categories:

$Y_s = 0$ Rock: sedimentary or basement rock or soil less than $10\,\mathrm{m}$ thick, 11 records.

$Y_s = 1$ Soil: alluvium or other soft material greater than $10\,\mathrm{m}$ thick, 59 records.

- Uses records from basement of buildings or from 'free-field'. Uses no more than seven records from same earthquake and no more than nine from a single site to minimize underestimation of calculated variance. Retains records which give a large distance and magnitude range.
- Notes that near-field ground motion governed by different physical laws than intermediate and far field so excludes near-field data, for example El Centro (19/5/1940) and Cholame-2, from Parkfield earthquake (28/6/1966)
- Considers a distance dependent site term but not statistically significant. Also uses a magnitude dependent site term and although it was statistically significant it did not reduce the scatter and also since largest magnitude for a rock site is 6.5, result may be biased.

2.20 A. Patwardhan, K. Sadigh, I.M. Idriss, R. Youngs (1978) reported in Idriss (1978)

- Ground-motion model is:

$$\ln y = \ln A + BM_s + E \ln[R + d \exp(f M_s)]$$

  where y is in $\mathrm{cm/s^2}$, $d = 0.864$ and $f = 0.463$ and for path A (rock): $A = 157$ (for median), $A = 186$ (for mean), $B = 1.04$ and $E = -1.90$, for path A (stiff soil): $A = 191$ (for median), $A = 224$ (for mean), $B = 0.823$ and $E = -1.56$ and for path B (stiff soil): $A = 284$ (for median), $A = 363$ (for mean), $B = 0.587$ and $E = -1.05$ (σ not given).

- Separate equations for two types of path:

  A Shallow focus earthquakes (California, Japan, Nicaragua and India), 63 records.

B Subduction (Benioff) zone earthquakes (Japan and South America), 23 earthquakes, $5.3 \leq M_s \leq 7.8$, 32 records.

- Use two site categories for path A earthquakes for which derive separate equations:

  1. Rock: 21 records.
  2. Stiff soil: 42 records.

  Use only stiff soil records for deriving subduction zone equation.

- Most earthquakes for path A have $5 \leq M_s \leq 6.7$.

- All data corrected. PGA for corrected Japanese and South American records much higher than uncorrected PGA.

2.21 Cornell *et al.* (1979)

- Ground-motion model is:

$$\ln A_p = a + bM_L + c\ln(R + 25)$$

  where A_p is in $\mathrm{cm/s^2}$, $a = 6.74$, $b = 0.859$, $c = -1.80$ and $\sigma = 0.57$.

- No more than 7 records from one earthquake to avoid biasing results.

- Records from basements of buildings or free-field.

2.22 Faccioli (1979)

- Ground-motion model is:

$$\log y = b_1 + b_2M + b_3\log(R + 25)$$

  where y is in $\mathrm{cm/s^2}$, $b_1 = 0.44$, $b_2 = 0.33$, $b_3 = -2.66$ and $\sigma = 0.12$.

- Uses data from three sedimentary rock sites (Somplago, San Rocco and Robic) because aim of study to provide zoning criteria as free as possible from influence of local conditions.

- Compares predictions and observations and find close fit, possibly because of restricted distance range.

- Note that use of simple functional form and r_{hypo} acceptable approximation because of short rupture lengths.

2.23 Faccioli & Agalbato (1979)

- Ground-motion model is:

$$\log y = b_1 + b_2M + b_3\log(R + \alpha)$$

  where y is in $\mathrm{cm/s^2}$, $b_1 = 1.59 \pm 0.69$, $b_2 = 0.25 \pm 0.03$, $b_3 = -0.79 \pm 0.12$, $\alpha = 0$ and $\sigma = 0.25$ for horizontal PGA and $b_1 = 1.38 \pm 1.89$, $b_2 = 0.24 \pm 0.09$, $b_3 = -0.78 \pm 0.25$ and $\sigma = 0.25$ for vertical PGA.

- Use two site classes:

  Soil Includes alluvium and moraine deposits of varying thicknesses and characteristics.

  Rock-like Includes limestone, dolomite, flysch and cemented conglomerates, even if heavily fractured, overlain by not more than 4–$5\,\mathrm{m}$ of alluvium.

  Use published and unpublished material for classification.

- Focal depths between 6 and $11\,\mathrm{km}$.

- Use data from Friuli 1976 mainshock and subsequent earthquakes from four networks including temporary stations (ENEL, CNEN, IZIIS and CEA/DSN). Data from ENEL, CNEN and IZIIS from RFT-250 and SMA-1 instruments and data from CEA/DSN from short-period seismographs. Some records not available in digital form so used reported PGAs.

- Almost all records from free-field stations.

- 58 PGAs from $r_{hypo} \leq 20\,\mathrm{km}$.

- $13\,\mathrm{cm/s^2} \leq PGA \leq 515\,\mathrm{cm/s}$ with 93% above $30\,\mathrm{cm/s^2}$.

- Best-recorded earthquake (mainshock) contributed 24 PGAs.

- One station contributed 17 PGAs.

- Also regresses just using data from mainshock.

- α is either 0 or 25 in regression. Prefer results with $\alpha = 0$ because smaller standard errors in b_3.

- Statistical tests show b_2 and b_3 are significantly different than 0.

- Also present coefficients for rock-like stations only and soil stations only. Find that effect of selection by site class does not greatly affect coefficients.

- Process a smaller set of records available in digitized form (76 horizontal components) using high-pass filter (cut-off and roll-off of 0.4–$0.8\,\mathrm{Hz}$) based on digitization noise. Note difficulty in standard processing due to high-frequency content and short durations. Use sampling rate of $100\,\mathrm{Hz}$. Find that corrected horizontal PGAs are on average 6% lower than uncorrected PGAs and 15% show difference larger than 10%. For vertical PGAs average difference is 12%. Develop equations based on this subset (for horizontal PGA $b_1 = 1.51 \pm 0.77$, $b_2 = 0.24 \pm 0.04$, $b_3 = 0.70 \pm 0.21$ and $\sigma = 0.24$). Note similarity to results for uncorrected PGAs.

- Also derive equation using only 39 PGAs from $r_{hypo} \leq 20\,\mathrm{km}$ and note weak magnitude and distance dependence. Compare to data from shallow soil sites at Forgaria-Cornino and Breginj and note that local site conditions can significantly modify bedrock motions even at close distances.

2.24 Aptikaev & Kopnichev (1980)

- Ground-motion model is:

$$\log A_e = a_1 M + a_2 \log R + a_3$$

where A_e is in $\mathrm{cm/s^2}$, for $A_e \geq 160\,\mathrm{cm/s^2}$ $a_1 = 0.28$, $a_2 = -0.8$ and $a_3 = 1.70$ and for $A_e < 160\,\mathrm{cm/s^2}$ $a_1 = 0.80$, $a_2 = -2.3$ and $a_3 = 0.80$ (σ not given).

- As a rule, PGA corresponds to S-wave.

- Use five source mechanism categories (about 70 records, 59 earthquakes from W. N. America including Hawaii, Guatemala, Nicaragua, Chile, Peru, Argentina, Italy, Greece, Romania, central Asia, India and Japan):

  1. Contraction faulting (uplift and thrust), about 16 earthquakes.
  2. Contraction faulting with strike-slip component, about 6 earthquakes.
  3. Strike-slip, about 17 earthquakes.
  4. Strike-slip with dip-slip component, about 6 earthquakes.
  5. Dip-slip, about 9 earthquakes.

- Use these approximately 70 records to derive ratios of mean measured, A_0, to predicted PGA, A_e, $\log(A_0/A_e)$, and for ratios of mean horizontal to vertical PGA, $\log A_h/A_v$, for each type of faulting. Use every earthquake with equal weight independent of number of records for each earthquake.

- Results are:

	Category 1	Category 2	Category 3	Category 4	Category 5
$\log A_0/A_e$	0.35 ± 0.13 (16)	0.11 ± 0.17 (5)	0.22 ± 0.08 (17)	0.06 ± 0.13 (6)	-0.06 ± 0.20 (9)
$\log A_h/A_v$	0.32 ± 0.13 (12)	0.32 ± 0.08 (5)	0.27 ± 0.07 (12)	0.18 ± 0.10 (5)	0.17 ± 0.11 (5)

where $\pm$ gives 0.7 confidence intervals and number in brackets is number of earthquakes used.

- Also calculate mean envelope increasing speed for P-wave amplitudes, A, obtained at teleseismic distances: $n = \mathrm{d} \ln A/\mathrm{d}t$, where t is time for P-wave arrival and try to relate to ratios for each type of faulting.

2.25 Blume (1980)

- Ground-motion model is:

$$a = b_1 \mathrm{e}^{b_2 M} (R + k)^{-b_3}$$

where a is in gal, for method using distance partitioning $b_1 = 18.4$, $b_2 = 0.941$, $b_3 = 1.27$ and $k = 25$ and for ordinary one-stage method $b_1 = 102$, $b_2 = 0.970$, $b_3 = 1.68$ and $k = 25$ (σ not given).

- Does not use PGA cutoff because PGA is, by itself, a poor index of damage in most cases.

- Mean magnitude is 5.4 and mean distance is $84.4\,\mathrm{km}$.

- Notes problem of regression leverage for some attenuation studies. Lots of data in fairly narrow distance band, e.g. records from San Fernando earthquake, can dominate regression and lead to biased coefficients.

- Divides data into ten distance bands (A-J) which are $10\,\mathrm{km}$ wide up to $60\,\mathrm{km}$ and then 60-$99.9\,\mathrm{km}$, 100–$139.9\,\mathrm{km}$, 140–$199.9\,\mathrm{km}$ and $\geq 200\,\mathrm{km}$. Fits $\log_{10} a = bM - c$ to data in each band and fits Ground-motion model to selected point set in M, R and a.

- Also fits equation using all data using normal least squares.

- Adds 52 records ($3.2 \leq M \leq 6.5$, $5 \leq R \leq 15\,\mathrm{km}$) and repeats; finds little change.

2.26 Iwasaki *et al.* (1980)

- Ground-motion model is:

$$\mathrm{PGA} = a_1 10^{a_2 M}(\Delta + 10)^{a_3}$$

  where PGA is in gal, for type I sites $a_1 = 46.0$, $a_2 = 0.208$ and $a_3 = -0.686$, for type II sites $a_1 = 24.5$, $a_2 = 0.333$ and $a_3 = -0.924$, for type III sites $a_1 = 59.0$, $a_2 = 0.261$ and $a_3 = -0.886$, for type IV sites $a_1 = 12.8$, $a_2 = 0.432$, $a_3 = -1.125$ and for all sites $a_1 = 34.1$, $a_2 = 0.308$ and $a_3 = -0.925$ (σ not given).

- Use four site categories:

Type I Tertiary or older rock (defined as bedrock) or diluvium with depth to bedrock, $H < 10\,\mathrm{m}$, 29 records.

Type II Diluvium with $H \geq 10\,\mathrm{m}$ or alluvium with $H < 10\,\mathrm{m}$, 74 records.

Type III Alluvium with $H < 25\,\mathrm{m}$ including soft layer (sand layer vulnerable to liquefaction or extremely soft cohesive soil layer) with thickness $< 5\,\mathrm{m}$, 130 records.

Type IV Other than above, usually soft alluvium or reclaimed land, 68 records.

- Select earthquakes with Richter magnitude ≥ 5.0, hypocentral depth $\leq 60\,\mathrm{km}$ and which include at least one record with PGA $\geq 50\,\mathrm{gals}$ ($0.5\,\mathrm{m/s^2}$). Exclude records with PGA $< 10\,\mathrm{gals}$ ($0.1\,\mathrm{m/s^2}$).

- All records for $M \geq 7.0$ are from distance $> 60\,\mathrm{km}$.

- Do regression separately for each soil category and also for combined data.

2.27 Matuschka (1980)

- Ground-motion model is:

$$Y_c = b_1 \mathrm{e}^{b_2 M}(R + b_4)^{-b_3}$$

  Coefficients unknown.

2.28 Ohsaki *et al.* (1980a)

- Ground-motion model is:

$$A = 10^{a_1 M - a_2 \log x + a_3}$$

  where A is in $\mathrm{cm/s^2}$, for horizontal PGA $a_1 = 0.440$, $a_2 = 1.381$ and $a_3 = 1.04$ and for vertical PGA $a_1 = 0.485$, $a_2 = 1.85$ and $a_3 = 1.38$ (σ not given).

- All records from free-field bedrock sites.

2.29 Campbell (1981)

- Ground-motion model is:

$$\mathrm{PGA} = a \exp(bM)[R + c_1 \exp(c_2 M)]^{-d}$$

  where PGA is in g, for unconstrained model $a = 0.0159$, $b = 0.868$, $c_1 = 0.0606$, $c_2 = 0.700$, $d = 1.09$ and $\sigma = 0.372$ (on natural logarithm) and for constrained model $a = 0.0185$, $b = 1.28$, $c_1 = 0.147$, $c_2 = 0.732$, $d = 1.75$ and $\sigma = 0.384$ (in terms of natural logarithm).

  Uses this functional form because capable of modelling possible nonlinear distance scaling in near field and because distance at which transition from near field to far field occurs probably proportional to fault rupture zone size.

- Considers six site classifications but does not model:

  A Recent alluvium: Holocene Age soil with rock $\geq 10\,\mathrm{m}$ deep, 71 records.

  B Pleistocene deposits: Pleistocene Age soil with rock $\geq 10\,\mathrm{m}$ deep, 22 records.

  C Soft rock: Sedimentary rock, soft volcanics, and soft metasedimentary rock, 14 records.

  D Hard rock: Crystalline rock, hard volcanics, and hard metasedimentary rock, 9 records.

  E Shallow soil deposits: Holocene or Pleistocene Age soil $< 10\,\mathrm{m}$ deep overlying soft or hard rock, 17 records. Not used in analysis.

  F Soft soil deposits: extremely soft or loose Holocene Age soils, e.g. beach sand or recent floodplain, lake, swamp, estuarine, and delta deposits, 1 record. Not used in analysis.

- Notes that data from areas outside western USA may be substantially different than those from western USA due to tectonics and recording practices but far outweighed by important contribution these data can make to understanding of near-source ground motion.

- Notes use of only near-source data has made differences in anelastic attenuation negligible to inherent scatter from other factors.

- Selects data from shallow tectonic plate boundaries generally similar to western N. America, deep subduction events excluded because of differences in travel paths and stress conditions.

- Selects data from instruments with similar dynamic characteristics as those used in USA to avoid bias, therefore excludes data from SMAC accelerographs in Japan.
- Selects data which meet these criteria:
    1. Epicentres known with an accuracy of $5\,\mathrm{km}$ or less, or accurate estimate of closest distance to fault rupture surface known.
    2. Magnitudes accurate to within 0.3 units.
    3. Distances were within 20, 30, and $50\,\mathrm{km}$ for magnitudes less than 4.75 between 4.75 and 6.25 and greater than 6.25 respectively. Only uses data from earthquakes with magnitude ≥ 5.0 because of greatest concern for most design applications.
    4. Hypocentres or rupture zones within $25\,\mathrm{km}$ of ground surface.
    5. PGA$\geq 0.2\,\mathrm{m/s}^2$ for one component, accelerographs triggered early enough to capture strong phase of shaking.
    6. Accelerograms either free-field, on abutments of dams or bridges, in lowest basement of buildings, or on ground level of structures without basements. Excluded Pacoima Dam record, from San Fernando (9/2/1971) earthquake due to topographic, high-frequency resonance due to large gradation in wave propagation velocities and amplification due to E-W response of dam.
- Well distributed data, correlation between magnitude and distance only 6%.
- Uses PGA from digitised, unprocessed accelerograms or from original accelerograms because fully processed PGAs are generally smaller due to the $0.02\,\mathrm{s}$ decimation and frequency band-limited filtering of records.
- Uses mean of two horizontal components because more stable peak acceleration parameter than either single components taken separately or both components taken together.
- Magnitude scale chosen to be generally consistent with M_w. Division point between using M_L and M_s varied between 5.5 and 6.5; finds magnitudes quite insensitive to choice.
- Notes r_{rup} is a statistically superior distance measure than epicentral or hypocentral and is physically consistent and meaningful definition of distance for earthquakes having extensive rupture zones.
- Does not use all data from San Fernando earthquake to minimize bias due to large number of records.
- Uses seven different weighting schemes, to control influence of well-recorded earthquakes (e.g. San Fernando and Imperial Valley earthquakes). Giving each record or each earthquake equal weight not reasonable representation of data. Uses nine distance dependent bins and weights each record by a relative weighting factor $1/n_{i,j}$, where $n_{i,j}$ is total number of recordings from ith earthquake in jth interval.
- Finds unconstrained coefficients and all coefficients statistically significant at 99%.
- Finds coefficients with d constrained to 1.75 (representative of far-field attenuation of PGA) and $c_2 = b/d$, which means PGA is independent of magnitude at the fault rupture surface. All coefficients statistically significant at 99%. Notes similarity between two models.

- Plots normalised weighted residuals against distance, magnitude[2] and predicted acceleration[2]. Finds that residuals uncorrelated, at 99%, with these variables.
- Normal probability plots, observed distribution of normalised weighted residuals and Kolmogorov-Smirnov test, at 90%, confirms that PGA can be accepted as being lognormally distributed.
- Finds effects of site geology, building size, instrument location and mechanism to be extensively interrelated so selects only records from free-field or small structures.
- Analyses all selected data, find sites of classes E and F significantly higher PGA , at 90% level, so removes records from E and F.
- Finds differences in PGA from other site categories to be negligible but notes that it cannot be extended to PGV, PGD, spectral ordinates or smaller magnitudes or further distances.
- Distribution with mechanism is: 69 from strike-slip, 40 from reverse, 5 from normal and 2 records from oblique. Finds that reverse fault PGAs are systematically higher, significant at 90%, than those from other fault types although size of bias is due to presence of data from outside N. America.
- Considers soil (A and B) records from small buildings (115 components) and in free-field and those obtained in lowest basement of large buildings (40 components). Finds PGA significantly lower, at 90% level, in large buildings.
- Finds topographic effects for 13 components used in final analysis (and for 11 components from shallow soil stations) to be significantly higher, at 90%, although states size of it may not be reliable due to small number of records.
- Removes Imperial Valley records and repeats analysis. Finds that saturation of PGA with distance is not strongly dependent on this single set of records. Also repeats analysis constraining $c_2 = 0$, i.e. magnitude independent saturation, and also constraining $c_1 = c_2 = 0$, i.e. no distance saturation, finds variance when no distance saturation is significantly higher, at 95%, than when there is saturation modelled.
- Finds that magnitude saturation effects in modelling near-source behaviour of PGA is important and c_2 is significantly greater than zero at levels of confidence exceeding 99%. Also variance is reduced when $c_2 \neq 0$ although not at 90% or above.
- Repeats analysis using distance to surface projection of fault, finds reduced magnitude saturation but similar magnitude scaling of PGA for larger events.

2.30 Chiaruttini & Siro (1981)

- Ground-motion model is:

$$\log a = b_0 + b_{AN} X_{AN} + b_{AB} X_{AB} + b_M M_L + b_d \log d$$

  where a is in $\mathrm{g}/100$, $b_0 = 0.04$, $b_{AN} = 0.24$, $b_{AB} = 0.23$, $b_M = 0.41$ and $b_d = -0.99$ (σ not given).

[2]Not shown in paper.

- Use three site categories for Friuli records, although note that information is rather superficial:

  ThA Alluvium with depth $> 20\,\mathrm{m}$, 36 records.

  Rl Rock-like: hard rock or stiff soil, 24[3] records.

  thA Alluvium-like with depth $\leq 20\,\mathrm{m}$: includes sites for which thickness of deposit is reported to be very small which accounts for a few metres of weathering of underlying bedrock, 60 records.

  Alpide belt records divided into two categories: rock-like (25 records) and alluvium-like (40 records).

- Use data from free-field instruments or from instruments in basements of small structures and divide data into three regions: those from 1976 Friuli shocks (120 records) $\Rightarrow X_{AN} = X_{AB} = 0$, those from 1972 Ancona swarm (40 records) $\Rightarrow X_{AN} = 1$ & $X_{AB} = 0$ and those from Alpide Belt (Azores to Pakistan excluding those from Friuli and Ancona) (64 records) $\Rightarrow X_{AN} = 0$ & $X_{AB} = 1$. Exclude records with PGA $< 0.15\,\mathrm{m/s^2}$ to avoid possible bias at low acceleration values.

- Assume average focal depth of $6\,\mathrm{km}$.

- Note some PGA values derived from velocity records which are retained because compatible with other data. No instrument corrections applied to Friuli records because correction does not substantially alter PGA.

- Use M_L because determined at short distances and allows homogenous determination from lowest values up to saturation at $M_L = 7.0$ and it is determined at frequencies of nearly $1\,\mathrm{Hz}$, close to accelerographic band.

- Perform regression on PGAs from each of the three regions and each soil types considered within that region.

- Group rock-like (R) and thick alluvium (ThA) records together for Friuli. Find b_d for Friuli equations derived for thin alluvium-like and rock and thick alluvium not significantly different but b_M is significantly different, at 95% level. Repeat analysis using only Tolmezzo records because of large scatter in residuals but decide it is in thA category.

- For Alpide belt equations find b_M is almost the same for Rl and Al records and the difference in b_d is less than standard error, thus repeat analysis using a dummy variable X_{Al} which equals 0 for Rl and 1 for Al records.

2.31 Joyner & Boore (1981)

- Ground-motion model is:

$$
\begin{aligned}
\log y &= \alpha + \beta \mathbf{M} - \log r + br \\
\text{where } r &= (d^2 + h^2)^{1/2}
\end{aligned}
$$

  where y is in g, $\alpha = -1.02$, $\beta = 0.249$, $b = -0.00255$, $h = 7.3$ and $\sigma = 0.26$.

- Use two site categories (not all records have category):

[3]Typographic error in their Table 1 because only 14 records are listed for rock-like sites

$S = 0$ Rock: sites described as granite, diorite, gneiss, chert, greywacke, limestone, sandstone or siltstone and sites with soil material less than 4 to $5\,\mathrm{m}$ thick overlying rock, 29 records. Indicate caution in applying equations for $\mathbf{M} > 6.0$ due to limited records.

$S = 1$ Soil: sites described as alluvium, sand, gravel, clay, silt, mud, fill or glacial outwash except where soil less than 4 to $5\,\mathrm{m}$ thick, 96 records.

- Restrict data to western North American shallow earthquakes, depth less than $20\,\mathrm{km}$, with $\mathbf{M} > 5.0$. Most records from earthquakes with magnitudes less than 6.6.
- Exclude records from base of buildings three or more storeys high and from abutments of dams.
- Exclude records associated with distances which had an uncertainty greater than $5\,\mathrm{km}$.
- Exclude records from distances greater than or equal to the shortest distance to an instrument which did not trigger.
- Six earthquakes recorded at only one station so not included in second stage regression.
- Include quadratic dependence term, $\gamma\mathbf{M}^2$, but not significant at 90% level so omitted.
- Include site term, cS, but not significant so omitted.
- Examine residuals against distance for difference magnitude ranges, no obvious differences in trends are apparent among the different magnitude classes.
- Consider a magnitude dependent $h = h_1 \exp(h_2[\mathbf{M} - 6.0])$ but reduction in variance not significant. Also prefer magnitude independent h because requires fewer parameters.
- Examine effect of removing records from different earthquakes from data.
- Examine effect of different h on residuals and b. Note coupling between h and b.
- Note coincidence of anelastic coefficient, b, and measured Q values. Also note similarity between h and proportions of depth of seismogenic zone in California.

2.32 Bolt & Abrahamson (1982)

- Ground-motion model is:

$$y = a\{(x + d)^2 + 1\}^c \mathrm{e}^{-b(x+d)}$$

  where y is in g, for $5 \leq \mathbf{M} < 6$ $a = 1.2$, $b = 0.066$, $c = 0.033$, $d = 23$ and standard error for one observation of $0.06\,\mathrm{g}$, for $6 \leq \mathbf{M} < 7$ $a = 1.2$, $b = 0.044$, $c = 0.042$, $d = 25$ and standard error for one observation of $0.10\,\mathrm{g}$, for $7 \leq \mathbf{M} \leq 7.7$ $a = 0.24$ $b = 0.022$, $c = 0.10$, $d = 15$ and standard error for one observation of $0.05\,\mathrm{g}$ and for $6 \leq \mathbf{M} \leq 7.7$ $a = 1.6$, $b = 0.026$, $c = -0.19$, $d = 8.5$ and standard error for one observation of $0.09\,\mathrm{g}$.
- Use data of Joyner & Boore (1981).
- Form of equation chosen to satisfy plausible physical assumptions but near-field behaviour is not determined from overwhelming contributions of far-field data.

- Apply nonlinear regression on y not on $\log y$ to give more weight to near-field values.
- Split data into four magnitude dependent groups: $5 \leq \mathbf{M} < 6$, $6 \leq \mathbf{M} < 7$, $7 \leq \mathbf{M} \leq 7.7$ and $6 \leq \mathbf{M} \leq 7.7$.
- Use form of equation and regression technique of Joyner & Boore (1981), after removing 25 points from closer than $8\,\mathrm{km}$ and find very similar coefficients to Joyner & Boore (1981). Conclude from this experiment and their derived coefficients for the four magnitude groups that using their form of equation predicted near-field accelerations are not governed by far-field data.
- Find no evidence of systematic increase in PGA near the source as a function of magnitude and that the large scatter prevents attaching significance to differences in near-field PGA which are predicted using their attenuation relations for different magnitude ranges.

2.33 Joyner & Boore (1982b) & Joyner & Boore (1988)

- Ground-motion model is:

$$\begin{aligned}\log y &= \alpha + \beta(M-6) + \gamma(M-6)^2 - p\log r + br + cS \\ r &= (d^2+h^2)^{1/2}\end{aligned}$$

  where y is in g, $\beta = 0.23$, $\gamma = 0$, $p = 1$, $b = -0.0027$, $c = 0$, $h = 8.0$ and $\sigma = 0.28$ and for randomly oriented component $\alpha = 0.43$ and for larger component $\alpha = 0.49$.

- Use same data and method as Joyner & Boore (1981), see Section 2.31, for PGA.
- Use data from shallow earthquakes, defined as those for which fault rupture lies mainly above a depth of $20\,\mathrm{km}$.

2.34 PML (1982)

- Ground-motion model is:

$$\ln(a) = C_1 + C_2 M + C_3 \ln[R + C_4 \exp(C_5 M)]$$

  where a is in g, $C_1 = -1.17$, $C_2 = 0.587$, $C_3 = -1.26$, $C_4 = 2.13$, $C_5 = 0.25$ and $\sigma = 0.543$.

- Use data from Italy (6 records, 6 earthquakes), USA (18 records, 8 earthquakes), Greece (13 records, 9 earthquakes), Iran (3 records, 3 earthquakes), Pakistan (3 records, 1 earthquake), Yugoslavia (3 records, 1 earthquake), USSR (1 record, 1 earthquake), Nicaragua (1 record, 1 earthquake), India (1 record, 1 earthquake) and Atlantic Ocean (1 record, 1 earthquake).
- Develop for use in UK.

2.35 Schenk (1982)

- Ground-motion model is:

$$\log A_{\mathrm{mean}} = aM - b \log R + c$$

where A_{mean} is in $\mathrm{cm/s^2}$, $a = 1.1143$, $b = 1.576$ and $c = 2.371$ (σ not given).

- Fits equation by eye because least squares method is often strictly dependent on marginal observations, particularly for little pronounced dependence.

2.36 Brillinger & Preisler (1984)

- Ground-motion model is:

$$A^{1/3} = a_1 + a_2 M + a_3 \ln(d^2 + a_4^2)$$

where A is in g, $a_1 = 0.432(0.072)$, $a_2 = 0.110(0.012)$, $a_3 = -0.0947(0.0101)$, $a_4 = 6.35(3.24)$, $\sigma_1 = 0.0351(0.0096)$ (inter-event) and $\sigma_2 = 0.0759(0.0042)$ (intra-event), where numbers in brackets are the standard errors of the coefficients.

- Use exploratory data analysis (EDA) and alternating conditional expectations (ACE) techniques.
- Firstly sought to determine functions $\theta(A)$, $\phi(M)$ and $\psi(d)$ so that $\theta(A) \doteq \phi(M)+\psi(d)$, i.e. an approximately additive relationship. Prefer additivity because of linearity, ease of interpolation and interpretation and departures from fit are more easily detected.
- Use ACE procedure to find model. For set of data, with response y_i and predictors w_i and x_i find functions to minimize: $\sum_{i=1}^{n}[\theta(y_i) - \phi(w_i) - \psi(x_i)]^2$ subject to $\sum \phi(w_i) = 0$, $\sum \psi(x_i) = 0$, $\sum \theta(y_i) = 0$ and $\sum \theta(y_i)^2 = n$. Search amongst unrestricted curves or unrestricted monotonic curves. Use EDA to select specific functional forms from the estimates of θ, ϕ and ψ at each data point.
- Do not use weighting because does not seem reasonable from statistical or seismological points of view.
- Do not want any individual earthquake, e.g. one with many records, overly influencing results.
- Note that because each earthquake has its own source characteristics its records are intercorrelated. Therefore use 'random effects model' which accounts for perculiarities of individual earthquakes and correlation between records from same event.
- On physical grounds, restrict θ, ϕ and ψ to be monotonic and find optimal transformation of magnitude is approximately linear, optimal transformation of distance is logarithmic and cube root is optimal for acceleration transformation.
- Note that need correlations between coefficients, which are provided, to attach uncertainties to estimated PGAs.
- Provide method of linearization to give 95% confidence interval for acceleration estimates.

- Also provide a graphical procedure for estimating accelerations that does not rely on an assumed functional form.
- Examine residual plots (not shown) and found a candidate for an outlying observation (the record from the Hollister 1974 earthquake of $0.011\,\mathrm{g}$ at $17.0\,\mathrm{km}$).
- Find that assumption of normality after transformation seems reasonable.

2.37 Joyner & Fumal (1984), Joyner & Fumal (1985) & Joyner & Boore (1988)

- Ground-motion model is:

$$\begin{aligned} \log y &= c_0 + c_1(\mathbf{M}-6) + c_2(\mathbf{M}-6)^2 + c_3\log r + c_4 r + S \\ \text{where } r &= (d^2+h^2)^{\frac{1}{2}} \\ \text{and: } S &= \begin{cases} 0 & \text{for rock site} \\ c_6\log\frac{V}{V_0} & \text{for soil site} \end{cases} \end{aligned}$$

  where y is in g, coefficients c_0 to c_4, h and σ are from Joyner & Boore (1981) and c_6 and V_0 are not significant at 90% level so do not report them.
- Use data of Joyner & Boore (1981).
- Continuous site classification for soil sites in terms of shear-wave velocity, V, to depth of one quarter wavelength of waves of period of concern. V measured down to depths of at least $30\,\mathrm{m}$ and then extrapolated using geological data. V known for 33 stations.
- Soil amplification factor based on energy conservation along ray tubes, which is a body wave argument and may not hold for long periods for which surface waves could be important. Does not predict resonance effects.
- Regress residuals, R_{ij}, w.r.t. motion predicted for rock sites on $\log R_{ij} = P_i + c_6 V_j$, where j corresponds to jth station and i to ith earthquake. Decouples site effects variation from earthquake-to-earthquake variation. Find unique intercept by requiring average site effect term calculated using shear-wave velocity to be same as that calculated using rock/soil classification.
- No significant, at 90%, correlation between residuals and V for PGA.
- Repeat regression on residuals using V and depth to underlying rock (defined as either shear-wave velocity $> 750\,\mathrm{m/s}$ or $> 1500\,\mathrm{m/s}$). Find no correlation.

2.38 Kawashima *et al.* (1984) & Kawashima *et al.* (1986)

- Ground-motion model is:

$$X(M,\Delta,\mathrm{GC}_i) = a(\mathrm{GC}_i)10^{b(\mathrm{GC}_i)M}(\Delta+30)^c$$

  where $X(M,\Delta,\mathrm{GC}_i)$ is in gal, $c=-1.218$, for group 1 sites $a(\mathrm{GC}_1)=987.4$, $b(\mathrm{GC}_1)=0.216$ and $\sigma=0.216$, for group 2 sites $a(\mathrm{GC}_2)=232.5$, $b(\mathrm{GC}_2)=0.313$ and $\sigma=0.224$ and for group 3 sites $a(\mathrm{GC}_3)=403.8$, $b(\mathrm{GC}_3)=0.265$ and $\sigma=0.197$.

- Use three site categories:

Group 1 Tertiary or older rock (defined as bedrock) or diluvium with $H < 10\,\mathrm{m}$ or fundamental period $T_G < 0.2\,\mathrm{s}$.

Group 2 Diluvium with $H \geq 10\,\mathrm{m}$, alluvium with $H < 10\,\mathrm{m}$ or alluvium with $H < 25\,\mathrm{m}$ including soft layer with thickness $< 5\,\mathrm{m}$ or fundamental period $0.2 < T_G < 0.6\,\mathrm{s}$.

Group 3 Other than above, normally soft alluvium or reclaimed land.

- Only includes free-field records with $M_{\mathrm{JMA}} \geq 5.0$ and focal depths $D_p < 60\,\mathrm{km}$. Excludes records from structures with first floor or basement.
- Records instrument corrected, because Japanese instruments substantially suppress high frequencies, considering accuracy of digitization for frequencies between $\frac{1}{3}$ and $12\,\mathrm{Hz}$.
- Note that M_{JMA} and Δ not necessarily most suitable parameters to represent magnitude and distance but only ones for all records in set.
- Note lack of near-field data for large magnitude earthquakes, approximately $\frac{3}{4}$ of records from $M_{\mathrm{JMA}} < 7.0$.
- Use $30\,\mathrm{km}$ in distance dependence term because focal depth of earthquakes with magnitudes between 7.5 and 8.0 are between 30 and $100\,\mathrm{km}$ so 30 is approximately half the fault length.
- Try equation: $\log X = f_1 + f_2 M + f_3 \log(\Delta+30) + f_4 D_p + f_5 M \log(\Delta+30) + f_6 M D_p + f_7 D_p \log(\Delta+30) + f_8 M^2 + f_9\{\log(\Delta+30)\}^2 + f_{10} D_p^2$ where f_i are coefficients to be found considering each soil category separately. Apply multiple regression analysis to 36 combinations of retained coefficients, f_i, and compute multiple correlation coefficient, R, and adjusted multiple correlation coefficient, R^*. Find that inclusion of more than three coefficients does not give significant increase in R^*, and can lead to unrealistic results. Conclude due to insufficient data.
- Consider a, b and c dependent and independent of soil type and examine correlation coefficient, R, and adjusted correlation coefficient, R^*. Find that c is not strongly dependent on soil type.
- Find match between normal distribution and histograms of residuals.

2.39 McCann Jr. & Echezwia (1984)

- Four Ground-motion models:

$$
\begin{aligned}
\log_{10} Y &= a + bM + d\log_{10}[(R^2+h^2)^{1/2}] \quad \text{Model I}\\
\log_{10} Y &= a + bM + d\log_{10}[R + c_1\exp(c_2 M)] \quad \text{Model II}\\
\log_{10} Y &= a + bM + d\log_{10}\left[\frac{c_1}{R^2} + \frac{c_2}{R}\right] + eR \quad \text{Model III}\\
\log_{10} Y &= a + bM + d\log_{10}[R+25] \quad \text{Model IV}
\end{aligned}
$$

where Y is in g, for model I $a = -1.320$, $b = 0.262$, $d = -0.913$, $h = 3.852$ and $\sigma = 0.158$, for model II $a = -1.115$, $b = 0.341$, $c_1 = 1.000$, $c_2 = 0.333$, $d = -1.270$ and $\sigma = 0.154$, for model III $a = -2.000$, $b = 0.270$, $c_1 = 0.968$, $c_2 = 0.312$, $d = 0.160$,

$e = -0.0105$ and $\sigma = 0.175$ and for model IV $a = 1.009$, $b = 0.222$, $d = -1.915$ and $\sigma = 0.174$.

- Note 25 in Model IV should not be assumed but should be found by regression.
- Note tectonics and travel paths may be different between N. American and foreign records but consider additional information in near field more relevant.
- Selection procedure composite of Campbell (1981) and Joyner & Boore (1981). Exclude data from buildings with more than two storeys.
- Weighted least squares, based on distance, applied to control influence of well recorded events (such as San Fernando and Imperial Valley). Similar to Campbell (1981)
- Test assumption that logarithm of residuals are normally distributed. Cannot disprove assumption.
- Variability between models not more than $\pm 20\%$ at distances $> 10\,\text{km}$ but for distances $< 1\,\text{km}$ up to $\pm 50\%$.

2.40 Schenk (1984)

- Ground-motion model is:

$$\log A_{\text{mean}} = aM - b \log R + c$$

where A_{mean} is in cm/s^2, $a = 0.37$, $b = 1.58$ and $c = 2.35$ (σ not given).

- Considers two site conditions but does not model:
  1. Solid
  2. Soft
- Fits equation by eye.
- States applicable approximately for: $R_{\text{lower}} \leq R \leq R_{\text{upper}}$ where $\log R_{\text{lower}} \doteq 0.1M + 0.5$ and $\log R_{\text{upper}} \doteq 0.35M + 0.4$, due to distribution of data.
- Notes great variability in recorded ground motions up to $R = 30\,\text{km}$ due to great influence of different site conditions.
- Notes for $M \leq 4$ source can be assumed spherical but for $M > 4$ elongated (extended) shape of focus should be taken into account.

2.41 Xu *et al.* (1984)

- Ground-motion model is:

$$\text{PGA} = a_1 \exp(a_2 M)(R + a_3)^{-a_4}$$

where PGA is in g, $a_1 = 0.1548$, $a_2 = 0.5442$, $a_3 = 8$ and $a_4 = 1.002$ (σ not given).

- All records from aftershocks of 1975 Haicheng earthquake and from 1976 Tangshan earthquake and aftershocks.

- Most records from earthquakes with magnitude less than 5.8 and from distances $< 30\,\mathrm{km}$.
- Exclude records with PGA $< 0.5\,\mathrm{m/s^2}$ to avoid too much contribution from far field.
- Due to small number of records simple regression technique justified.
- States valid for $4 \le M \le 6.5$ and $R \le 100\,\mathrm{km}$.
- Also use 158 records from western N. America to see whether significantly different than N. Chinese data. Derive equations using both western N. American and N. Chinese data and just western N. American data and find that predicted PGAs are similar, within uncertainty.
- Insufficient data to find physically realistic anelastic term.

2.42 Brillinger & Preisler (1985)

- Ground-motion model is:

$$\begin{aligned} \log A &= a_1 + a_2 M - \log r + a_3 r \\ \text{where} \quad r^2 &= d^2 + a_4^2 \end{aligned}$$

  where A is in g, $a_1 = -1.229(0.196)$, $a_2 = 0.277(0.034)$, $a_3 = -0.00231(0.00062)$, $a_4 = 6.650(2.612)$, $\sigma_1 = 0.1223(0.0305)$ (inter-event) and $\sigma = 0.2284(0.0127)$ (intra-event), where numbers in brackets are the standard errors of the coefficients.
- Provide algorithm for random effects regression.
- Note that the functional form adopted in Brillinger & Preisler (1984) is strictly empirical and hence repeat analysis using functional form of Joyner & Boore (1981), which is based on physical reasoning.
- Note that need correlations between coefficients, which are provided, to attach uncertainties to estimated PGAs.

2.43 Kawashima *et al.* (1985)

- Use very similar data to Kawashima *et al.* (1984); do not use some records because missing due to recording and digitizing processes. Use equation and method (although do not check all 36 combinations of forms of equation) used by Kawashima *et al.* (1984), see section 2.38.
- $X(M, \Delta, \mathrm{GC}_i)$ is in gal. Coefficients are: $c = -1.190$ and for ground group 1 $a = 117.0$ and $b = 0.268$ and for ground group 2 $a = 88.19$ and $b = 0.297$ and for group ground 3 $a = 13.49$ and $b = 0.402$ with $\sigma = 0.253$.

2.44 Peng *et al.* (1985b)

- Ground-motion model is:

$$\log_{10} a = A + BM + C \log_{10} R + DR$$

where a is in $\mathrm{cm/s^2}$, for N.E. China $A = -0.474$, $B = 0.613$, $C = -0.873$ and $D = -0.00206$ (σ not given) and for S.W. China $A = 0.437$, $B = 0.454$, $C = -0.739$ and $D = -0.00279$ (σ not given).

- Consider two site conditions for NE records but do not model:
    1. Rock: 28 records.
    2. Soil: 45 records.
- Consider all records to be free-field.
- Note that Chinese surface-wave magnitude, M, is different than M_s and may differ by 0.5 or more. Use m_b or M_s and find larger residuals.
- Most records from $M \leq 5.8$.
- Note isoseismals are not elongated for these earthquakes so use of another distance measure will not change results by much.
- Also derives equation for SW China ($3.7 \leq M \leq 7.2$, $6.0 \leq R \leq 428.0\,\mathrm{km}$ all but one record $\leq 106.0\,\mathrm{km}$, 36 records from 23 earthquakes) and note difference between results from NE China although use less data.
- Note that some scatter may be due to radiation pattern.
- Note that data is from limited distance range so need more data to confirm results.

2.45 Peng *et al.* (1985a)

- Ground-motion model is:

$$\begin{aligned}\log A_m &= a_1 + a_2 M - \log R - a_3 R \\ R &= \sqrt{d^2 + h^2}\end{aligned}$$

where A_m is g, $a_1 = -1.49$, $a_2 = 0.31$, $a_3 = 0.0248$, $h = 9.4\,\mathrm{km}$ and $\sigma = 0.32$ (for horizontal components) and $a_1 = -1.92$, $a_2 = 0.29$, $a_3 = 0.0146$, $h = 6.7\,\mathrm{km}$ and $\sigma = 0.36$ (for vertical components).

- Data from experimental strong-motion array consisting of 12 Kinemetrics PDR-1 instruments deployed in the epicentral area of the $M_s = 7.8$ Tangshan earthquake of 28th July 1976. Provide details of site geology at each station; most stations are on soil.
- Records from earthquakes recorded by only one station were excluded from analysis.
- Note that equations are preliminary and more refined equations await further studies of magnitudes and distances used in analysis.
- Note that high anelastic attenuation coefficient may be due to biases introduced by the distribution in magnitude-distance space and also because of errors in magnitude and distances used.

2.46 PML (1985)

- Ground-motion model is:

$$\ln(a) = C_1 + C_2 M + C_3 \ln[R + C_4 \exp(C_5 M)] + C_6 F$$

  where a is in g, $C_1 = -0.855$, $C_2 = 0.46$, $C_3 = -1.27$, $C_4 = 0.73$, $C_5 = 0.35$, $C_6 = 0.22$ and $\sigma = 0.49$.

- Use data from Italy (47 records, 9 earthquakes), USA (128 records, 18 earthquakes), Greece (11 records, 8 earthquakes), Iran (2 records, 2 earthquakes), Yugoslavia (7 records, 2 earthquake), Nicaragua (1 record, 1 earthquake), New Zealand (3 records, 3 earthquakes), China (2 records, 2 earthquakes) and Canada (2 records, 1 earthquake).

- Develop for use in UK.

- Select earthquakes with $M_s < 7$ and $R \leq 40\,\mathrm{km}$.

- Focal depths $< 40\,\mathrm{km}$.

- Use two source mechanism categories (40 records have no source mechanism given):

$F = 0$ Strike-slip and normal, 85 records.

$F = 1$ Thrust, 78 records.

- Also derive equation not considering source mechanism, i.e. $C_6 = 0$.

2.47 McCue (1986)

- Ground-motion model is:

$$A = a_1(\mathrm{e}^{a_2 M_L})(d_h)^{a_3}$$

  where A is in g, $a_1 = 0.00205$, $a_2 = 1.72$ and $a_3 = -1.58$ (σ not given).

2.48 C.B. Crouse (1987) reported in Joyner & Boore (1988)

- Ground-motion model is:

$$\ln y = a + bM_s + cM_s^2 + d\ln(r + 1) + kr$$

  where y is in gal, $a = 2.48456$, $b = 0.73377$, $c = -0.01509$, $d = -0.50558$, $k = -0.00935$ and $\sigma = 0.58082$.

- Records from deep soil sites (generally greater than $60\,\mathrm{m}$ in thickness).

- Data from shallow crustal earthquakes.

2.49 Krinitzsky *et al.* (1987) & Krinitzsky *et al.* (1988)

- Ground-motion model is (for shallow earthquakes):

$$\log A = a_1 + a_2 M - \log r + a_3 r$$

where A is in $\mathrm{cm/s^2}$, $a_1 = 1.23$ (for hard sites), $a_1 = 1.41$ (for soft sites), $a_2 = 0.385$ and $a_3 = -0.00255$ (σ is not given).

Ground-motion model is (for subduction zone earthquakes):

$$\log A = b_1 + b_2 M - \log \sqrt{r^2 + 100^2} + b_3 r$$

where A is in $\mathrm{cm/s^2}$, $b_1 = 2.08$ (for hard sites), $b_1 = 2.32$ (for soft sites), $b_2 = 0.35$ and $b_3 = -0.0025$ (σ is not given).

- Use four site categories:

  1 Rock
  2 Stiff soil
  3 Deep cohesionless soil ($\geq 16\,\mathrm{m}$)
  4 Soft to medium stiff clay ($\geq 16\,\mathrm{m}$)

  Categories 1 and 2 are combined into a hard (H) class and 3 and 4 are combined into a soft (S) class. This boundary established using field evidence at a shear-wave velocity of $400\,\mathrm{m/s}$ and at an SPT N count of 60.

- Use data from ground floors and basements of small or low structures (under 3 stories) because believe that small structures have little effect on recorded ground motions.

- Separate earthquakes into shallow ($h \leq 19\,\mathrm{km}$) and subduction ($h \geq 20\,\mathrm{km}$) because noted that ground motions have different characteristics.

- Use epicentral distance for Japanese data because practical means of representing deep subduction earthquakes with distant and imprecise fault locations.

- Do not use rupture distance or distance to surface projection of rupture because believe unlikely that stress drop and peak motions will occur with equal strength along the fault length and also because for most records fault locations are not reliably determinable.

- Note that there is a paucity of data but believe that the few high peak values observed (e.g. Pacoima Dam and Morgan Hill) cannot be dismissed without the possibility that interpretations will be affected dangerously.

- For subduction equations, use records from Japanese SMAC instruments that have not been instrument corrected, even though SMAC instruments show reduced sensitivity above $10\,\mathrm{Hz}$, because ground motions $> 10\,\mathrm{Hz}$ are not significant in subduction earthquakes. Do not use records from SMAC instruments for shallow earthquakes because high frequency motions may be significant.

- Examine differences between ground motions in extensional (strike-slip and normal faulting) and compressional (reverse) regimes for shallow earthquakes but do not model. Find that the extensional ground motions seem to be higher than compressional motions, which suggest is because rupture propagation comes closer to ground surface in extensional faults than in compressional faults.

- Group records into $1\,M$ unit intervals and plot ground motions against distance. When data is numerous enough the data points are encompassed in boxes (either one, two or three) that have a range equal to the distribution of data. The positions of the calculated values within the boxes were used as guides for shaping appropriate curves. Initially curves developed for $M = 6.5$ were there is most data and then these were extended to smaller and larger magnitudes.

2.50 Sabetta & Pugliese (1987)

- Ground-motion model is:

$$\log y = \boldsymbol{a} + \boldsymbol{b}M - \log(R^2 + \boldsymbol{h}^2)^{1/2} + \boldsymbol{e}S$$

  where y is in g and for distance to surface projection of fault $\boldsymbol{a} = -1.562$, $\boldsymbol{b} = 0.306$, $\boldsymbol{e} = 0.169$, $\boldsymbol{h} = 5.8$ and $\sigma = 0.173$.

- Use two site categories:

$S = 0$ Stiff and deep soil: limestone, sandstone, siltstone, marl, shale and conglomerates ($V_s > 800\,\mathrm{m/s}$) or depth of soil, H, $> 20\,\mathrm{m}$, 74 records.

$S = 1$ Shallow soil: depth of soil, H, $5 \leq H \leq 20\,\mathrm{m}$, 21 records.

- Select records which satisfy these criteria:

  1. Reliable identification of the triggering earthquake.
  2. Magnitude greater than 4.5 recorded by at least two stations.
  3. Epicentres determined with accuracy of $5\,\mathrm{km}$ or less.
  4. Magnitudes accurate to within 0.3 units.
  5. Accelerograms from free-field. Most are from small electric transformer cabins, 4 from one- or two-storey buildings with basements and 5 from near abutments of dams.

- Depths between 5.0 and $16.0\,\mathrm{km}$ with mean $8.5\,\mathrm{km}$.

- Focal mechanisms are: normal and oblique (7 earthquakes, 48 records), thrust (9 earthquakes, 43 records) and strike-slip (1 earthquake, 4 records).

- Notes lack of records at short distances from large earthquakes.

- Records baseline-, instrument-corrected and filtered with cutoff frequencies determined by visual inspection in order to maximise signal to noise ratio within band. Cutoff frequencies ranged from 0.2 to $0.4\,\mathrm{Hz}$ and from 25 to $35\,\mathrm{Hz}$. This correction routine thought to provide reliable estimates of PGA so uncorrected PGA do not need to be used.

- For well separated multiple shocks, to which magnitude and focal parameters refer, use only first shock.

- Magnitude scale assures a linear relationship between logarithm of PGA and magnitude and avoids saturation effects of M_L.

- Distance to surface projection of fault rupture thought to be a more physically consistent definition of distance for earthquakes having extensive rupture zones and is easier to predict for future earthquakes. Also reduces correlation between magnitude and distance.
- Use Exploratory Data Analysis using the ACE procedure to find transformation functions of distance, magnitude and PGA.
- Include anelastic attenuation term but it is positive and not significant.
- Include magnitude dependent $\boldsymbol{h}$ equal to $\boldsymbol{h_1} \exp(\boldsymbol{h_2} M)$ but find $\boldsymbol{h_2}$ not significantly different than zero. Note distribution of data makes test not definitive.
- Find geometric attenuation coefficient, $\boldsymbol{c}$, is close to -1 and highly correlated with $\boldsymbol{h}$ so constrain to -1 so less coefficients to estimate.
- Consider deep soil sites as separate category but find difference between them and stiff sites is not significant.
- Also use two-stage method but coefficients and variance did not change significantly with respect to those obtained using one-stage method, due to uniform distribution of recordings among earthquakes.
- Find no significant trends in residuals, at 99% level and also no support for magnitude dependent shape for attenuation curves.
- Exclude records from different seismotectonic and geological regions and repeat analysis. Find that predicted PGA are similar.
- Plot residuals from records at distances $15\,\mathrm{km}$ or less against magnitude; find no support for magnitude dependence of residuals.
- Note some records are affected by strong azimuthal effects, but do not model them because they require more coefficients to be estimated, direction of azimuthal effect different from region to region and azimuthal effects have not been used in other relationships.

2.51 K. Sadigh (1987) reported in Joyner & Boore (1988)

- Ground-motion model is:

$$\ln y = a + b\mathbf{M} + c_1(8.5 - \mathbf{M})^{c_2} + d \ln[r + h_1 \exp(h_2\mathbf{M})]$$

  where y is in g. For strike-slip earthquakes: $b = 1.1$, $c_1 = 0$, $c_2 = 2.5$, for PGA at soil sites $a = -2.611$ and $d = -1.75$, for $\mathbf{M} < 6.5$ $h_1 = 0.8217$, $h_2 = 0.4814$ and for $\mathbf{M} \geq 6.5$ $h_1 = 0.3157$ and $h_2 = 0.6286$, for PGA at rock sites $a = -1.406$ and $d = -2.05$, for $\mathbf{M} < 6.5$ $h_1 = 1.353$ and $h_2 = 0.406$ and for $\mathbf{M} \geq 6.5$ $h_1 = 0.579$ and $h_2 = 0.537$. For reverse-slip increase predicted values by 20%. For $\mathbf{M} < 6.5$ $\sigma = 1.26 - 0.14\mathbf{M}$ and for $\mathbf{M} \geq 6.5$ $\sigma = 0.35$.

- Uses two site categories:

  1. Soil

   2. Rock

- Use two source mechanism categories:
   1. Strike-slip
   2. Reverse-slip
- Supplement data with significant recordings of earthquakes with focal depths $< 20\,\mathrm{km}$ from other parts of world.
- Different equations for $\mathbf{M} < 6.5$ and $\mathbf{M} \geq 6.5$.

2.52 Singh *et al.* (1987)

- Ground-motion model is:

$$\log y_{\max} = \alpha M_s - c \log R + \beta$$

  where $y_{\max}$ is in $\mathrm{cm/s^2}$, $\alpha = 0.429$, $c = 2.976$, $\beta = 5.396$ and $\sigma = 0.15$.

  More complicated functional form unwarranted due to limited distance range.

- Depths between 15 and $20\,\mathrm{km}$.
- Only use data from a single firm site (Ciudad Universitaria), on a surface layer of lava flow or volcanic tuff.
- Only records from coastal earthquakes.
- Residuals plotted against distance, no trends seen.
- Give amplification factor for lake bed sites (25 to $80\,\mathrm{m}$ deposit of highly compressible, high water content clay underlain by resistant sands), but note based on only a few sites so not likely to be representative of entire lake bed.

2.53 Algermissen *et al.* (1988)

- Ground-motion model is:

$$\ln(A) = a_1 + a_2 M_s + a_3 \ln(R) + a_4 R$$

  where A is in g, $a_1 = -1.987$, $a_2 = 0.604$, $a_3 = -0.9082$, $a_4 = -0.00385$ and $\sigma = 0.68$.

2.54 Annaka & Nozawa (1988)

- Ground-motion model is:

$$\log A = C_m M + C_h H - C_d \log(R + A \exp BM) + C_o$$

  where A is in $\mathrm{cm/s^2}$, A and B so PGA becomes independent of magnitude at fault rupture, H is depth of point on fault plane when R becomes closest distance to fault plane, $C_m = 0.627$, $C_h = 0.00671$, $C_d = 2.212$, $C_o = 1.711$ and $\sigma = 0.211$.

- Focal depths $< 100\,\mathrm{km}$.
- Convert records from sites with $V_s < 300\,\mathrm{m/s}$ into records from sites with $V_s > 300\,\mathrm{m/s}$ using 1-D wave propagation theory.
- Introduce term $C_h H$ because it raises multiple correlation coefficient for PGA.
- Note equations apply for site where $300 \leq V_s \leq 600\,\mathrm{m/s}$.

2.55 K.W. Campbell (1988) reported in Joyner & Boore (1988)

- Ground-motion model is:

$$\begin{aligned} \ln y &= a + bM + d\ln[r + h_1 \exp(h_2 M)] + s \\ \text{where } s &= e_1K_1 + e_2K_2 + e_3K_3 + e_4K_4 + e_5K_5 + e_6(K_4 + K_5)\tanh(e_7 r) \end{aligned}$$

  where y is in g, $a = -2.817$, $b = 0.702$, $d = -1.20$, $h_1 = 0.0921$, $h_2 = 0.584$, $e_1 = 0.32$, $e_2 = 0.52$, $e_3 = 0.41$, $e_4 = -0.85$, $e_5 = -1.14$, $e_6 = 0.87$, $e_7 = 0.068$ and $\sigma = 0.30$.

- Uses two site categories:

$K_3 = 1$ Soils $\leq 10\,\mathrm{m}$ deep.

$K_3 = 0$ Other.

- Uses three embedment categories:

$K_4 = 1$, $K_5 = 0$ Basements of buildings 3–9 storeys.

$K_5 = 1$, $K_4 = 0$ Basements of buildings ≥ 10 storeys.

$K_4 = 0$, $K_5 = 0$ Other.

- Selects data using these criteria:
  1. Largest horizontal component of peak acceleration was $\geq 0.02\,\mathrm{g}$ [$\geq 0.2\,\mathrm{m/s^2}$].
  2. Accelerograph triggered early enough to record strongest phase of shaking.
  3. Magnitude of earthquake was ≥ 5.0.
  4. Closest distance to seismogenic rupture was < 30 or $< 50\,\mathrm{km}$, depending on whether magnitude of earthquake was < 6.25 or > 6.25.
  5. Shallowest extent of seismogenic rupture was $\leq 25\,\mathrm{km}$.
  6. Recording site located on unconsolidated deposits.
- Excludes records from abutments or toes of dams.
- Derives two equations: unconstrained (coefficients given above) and constrained which includes a anelastic decay term kr which allows equation to be used for predictions outside near-source zone (assumes $k = -0.0059$ for regression, a value appropriate for region of interest should be chosen).
- Uses two source mechanism categories:

$K_1 = 0$ Strike-slip.

$K_1 = 1$ Reverse.

- Uses two directivity categories:

$K_2 = 1$ Rupture toward site.

$K_2 = 0$ Other.

2.56 Fukushima *et al.* (1988) & Fukushima & Tanaka (1990)

- Ground-motion model is:

$$\log A = aM - \log(R + c10^{aM}) - bR + d$$

  where A is in $\mathrm{cm/s^2}$, $a = 0.41$, $b = 0.0034$, $c = 0.032$, $d = 1.30$ and $\sigma = 0.21$.

- Use four site categories for some Japanese stations (302 Japanese records not classified):

  1. Rock: 41 records
  2. Hard: ground above Tertiary period or thickness of diluvial deposit above bedrock $< 10\,\mathrm{m}$, 44 records.
  3. Medium: thickness of diluvial deposit above bedrock $> 10\,\mathrm{m}$, or thickness of alluvial deposit above bedrock $< 10\,\mathrm{m}$, or thickness of alluvial deposit $< 25\,\mathrm{m}$ and thickness of soft deposit is $< 5\,\mathrm{m}$, 66 records.
  4. Soft soil: other soft ground such as reclaimed land, 33 records.

- Use 1100 mean PGA values from 43 Japanese earthquakes ($6.0 \leq M_{\mathrm{JMA}} \leq 7.9$, focal depths $\leq 30\,\mathrm{km}$) recorded at many stations to investigate one and two-stage methods. Fits $\log A = c - b \log X$ (where X is hypocentral distance) for each earthquake and computes mean of b, $\bar{b}$. Also fits $\log A = aM - b^* \log X + c$ using one-stage method. Find that $\bar{b} > b^*$ and shows that this is because magnitude and distance are strongly correlated (0.53) in data set. Find two-stage method of Joyner & Boore (1981) very effective to overcome this correlation and use it to find similar distance coefficient to $\bar{b}$. Find similar effect of correlation on distance coefficient for two other models: $\log A = aM - b\log(\Delta + 30) + c$ and $\log A = aM - \log X - bX + c$, where Δ is epicentral distance.

- Japanese data selection criteria: focal depth $< 30\,\mathrm{km}$, $M_{\mathrm{JMA}} > 5.0$ and predicted PGA $\geq 0.1\,\mathrm{m/s^2}$. US data selection criteria: $d_r \leq 50\,\mathrm{km}$, use data from Campbell (1981).

- Because a affects distance and magnitude dependence, which are calculated during first and second steps respectively use an iterative technique to find coefficients. Allow different magnitude scaling for US and Japanese data.

- For Japanese data apply station corrections before last step in iteration to convert PGAs from different soil conditions to standard soil condition using residuals from analysis.

- Two simple numerical experiments performed. Firstly a two sets of artificial acceleration data was generated using random numbers based on attenuation relations, one with high distance decay and which contains data for short distance and one with lower distance decay, higher constant and no short distance data. Find that the overall equation from regression analysis has a smaller distance decay coefficient than individual coefficients for each line. Secondly find the same result for the magnitude dependent coefficient based on similar artificial data.

- Exclude Japanese data observed at long distances where average acceleration level was predicted (by using an attenuation relation derived for the Japanese data) to be less than the trigger level (assume to be about $0.05\,\mathrm{m/s^2}$) plus one standard deviation (assume to be 0.3), i.e. $0.1\,\mathrm{m/s^2}$, to avoid biasing results and giving a lower attenuation rate.

- Use the Japanese data and same functional form and method of Joyner & Boore (1981) to find an attenuation relation; find the anelastic coefficient is similar so conclude attenuation rate for Japan is almost equal to W. USA.

- Find difference in constant, d, between Japanese and W. USA PGA values.

- Plot residuals against distance and magnitude and find no bias or singularity.

2.57 Gaull (1988)

- Ground-motion model is:

$$\log \mathrm{PGA} = [(a_1 \log R + a_2)/a_3](M_L - a_4) - a_5 \log R - a_6 R + a_7$$

  where PGA is in $\mathrm{m/s^2}$, $a_1 = 5$, $a_2 = 3$, $a_3 = 20$, $a_4 = 6$, $a_5 = 0.77$, $a_6 = 0.0045$ and $a_7 = 1.2$ (σ not given).

- Considers three site categories but does not model:

  1. Rock: 6 records
  2. Alluvium: 5 records
  3. Average site: 10 records

- Most records from earthquakes with magnitudes about 3 and most from distances below about $20\,\mathrm{km}$.

- Band pass filter records to get PGA associated with waves with periods between 0.1 and $0.5\,\mathrm{s}$ because high frequency PGA from uncorrected records not of engineering significance.

- Adds 4 near source ($5 \leq R \leq 10\,\mathrm{km}$) records from US, Indian and New Zealand earthquakes with magnitudes between 6.3 and 6.7 to supplement high magnitude range.

- Add some PGA points estimated from intensities associated with 14/10/1968 $M_L = 6.9$ Meckering earthquake in Western Australia.

- Plot 6 records from one well recorded event with $M_L = 4.5$ and fit an attenuation curve of form $\log \mathrm{PGA} = b_1 - b_2 \log R - b_3 R$ by eye. Plot PGA of all records with $2 \leq R \leq 20\,\mathrm{km}$ against magnitude, fit an equation by eye. Use these two curves to normalise all PGA values to $M_L = 4.5$ and $R = 5\,\mathrm{km}$ from which estimates attenuation relation.

2.58 McCue *et al.* (1988)

- Ground-motion model is:

$$A = a(\exp(bM))\left(\frac{R}{R_0}+c\right)^{-d}$$

  where A is in g, $\ln a = -5.75$, $b = 1.72$, $c = 0$, $d = 1.69$ and $R_0 = 1$ (σ not given).

- Few records from free-field, most are in dams or special structures.,
- Because only 62 records, set $R_0 = 1$ and $c = 0$.
- Most records from earthquakes with M_L between 1.5 and 2.0.
- Maximum PGA in set $3.05\,\mathrm{m/s^2}$.
- Nonuniform distribution of focal distances. One quarter of records from same hypocentral distance. Therefore plot PGA of these records against magnitude ($1.2 \lesssim M_L \lesssim 4.3$ most less than 2.1) to find b. Then plot $bM - \ln A$ against $\ln(R/R_0)$ for all records to find a and d.
- Notes limited data.

2.59 Petrovski & Marcellini (1988)

- Ground-motion model is:

$$\ln(a) = b_1' + b_2M + b_3\ln(R + c)$$

  where a is in $\mathrm{cm/s^2}$, $b_1' = 6.4830$, $b_2 = 0.5438$, $b_3 = -1.3330$, $c = 20\,\mathrm{km}$ and $\sigma = 0.6718$ (for horizontal PGA) and $b_1 = 5.6440$, $b_2 = 0.5889$, $b_3 = -1.3290$, $c = 20\,\mathrm{km}$ and $\sigma = 0.6690$ (for vertical PGA) (also give coefficients for other choices of c).

- Data from ‘moderate’ soil conditions.
- Data mainly from SMA-1s but 17 from RFT-250s.
- Data from northern Greece (5 records, 4 stations, 3 earthquakes), northern Italy (45 records, 18 stations, 20 earthquakes) and former Yugoslavia (70 records, 42 stations, 23 earthquakes).
- Data from free-field or in basements of structures.
- Select records from earthquakes with $3 \leq M \leq 7$. Most earthquakes with $M \leq 5.5$. 4 earthquakes (4 records) with $M \leq 3.5$, 20 (27 records) with $3.5 < M \leq 4.5$, 13 (25 records) with $4.5 < M \leq 5.5$, 8 (50 records) with $5.5 < M \leq 6.5$ and 1 (14 records) with $M > 6.5$.
- Select records from earthquakes with $h \leq 40\,\mathrm{km}$. Most earthquakes with $h \leq 10\,\mathrm{km}$. 6 earthquakes with $h \leq 5\,\mathrm{km}$, 30 with $5 < h \leq 10\,\mathrm{km}$, 5 with $10 < h \leq 20\,\mathrm{km}$, 4 with $20 < h \leq 30\,\mathrm{km}$ and 1 with $h > 30$.
- Select records that satisfied predetermined processing criteria so that their amplitude would be such as to give negligible errors after processing.

- Select records to avoid concentration of records w.r.t. certain sites, magnitudes, hypocentral distances or earthquakes. Most well-recorded earthquakes is 15/4/1979 Montenegro earthquake with 14 records.
- Try values of c between 0 and $40\,\mathrm{km}$. Find standard deviation does not vary much for different choices.
- Test assumption of the log-normal probability distribution of data using graph in a coordinate system for log-normal distribution of probability, by χ^2 test and by the Kolmogorov-Smirnov test (not shown). Find assumption is acceptable.

2.60 Tong & Katayama (1988)

- Ground-motion model is:

$$\log \bar{A} = \alpha M - \beta \log(\Delta + 10) + \gamma T + \delta$$

  where $\bar{A}$ is in gal, T is predominant period of site, $\alpha = 0.509$, $\beta = 2.32$, $\gamma = 0.039$ and $\delta = 2.33$ (σ not given).
- Correlation coefficient between magnitude and distance is 0.84, so magnitude and distance cannot be considered independent, so attenuation rate, β, is difficult to find.
- First step fit $\log \bar{A} = -\beta_i \log(\Delta + 10) + \delta_i$ to each earthquake. Define reliability parameter, $\psi_i = N_i R_i^2$, where N_i is degrees of freedom for i earthquake and R_i is correlation coefficient. Plot ψ_i against β_i and find attenuation rate scattered, between -6 and 9, for $\psi_i < 1$ (Group B) and for $\psi_1 > 1$ attenuation rate converges (Group U).
- Group B includes earthquakes with focal depths $> 388\,\mathrm{km}$, earthquakes with small magnitudes and records from distances $\approx 100\,\mathrm{km}$, earthquakes with records from great distances where spread of distances is small, earthquakes recorded by only 3 stations and earthquakes with abnormal records. Exclude these records.
- Apply multiple regression on Group U to find α, β, γ and δ simultaneously. Also fix $\beta = \sum \psi_i \beta_i / \sum \psi_i$ and find α, γ and δ. Find different coefficients but similar correlation coefficient. Conclude due to strong correlation between M and Δ so many regression planes exist with same correlation coefficient.
- Perform Principal Component Analysis (PCA) on $\log A$, M, $\log(\Delta + 10)$, T and $\log \bar{A}/A$ and find that equation found by fixing β is not affected by ill-effect of correlation between M and Δ.
- Omit T from regression and find little effect in estimation.

2.61 Yamabe & Kanai (1988)

- Ground-motion model is:

$$\begin{aligned} \log_{10} a &= \beta - \nu \log_{10} x \\ \text{where } \beta &= b_1 + b_2 M \\ \text{and: } \nu &= c_1 + c_2 M \end{aligned}$$

  where a is in gal, $b_1 = -3.64$, $b_2 = 1.29$, $c_1 = -0.99$ and $c_2 = 0.38$ (σ not given).

- Focal depths between 0 and $130\,\mathrm{km}$.
- Regress recorded PGA of each earthquake, i, on $\log_{10} a = \beta_i - \nu_i \log_{10} x$, to find β_i and ν_i. Then find b_1 and b_2 from $\beta = b_1 + b_2 M$ and c_1 and c_2 from $\nu = c_1 + c_2 M$.
- Also consider $\nu = d_1 \beta$.
- Find β and ν from 6 earthquakes (magnitudes between 5.4 and 6.1) from Tokyo-Yokohama area are much higher than for other earthquakes, so ignore them. Conclude that this is due to effect of buildings on ground motion.

2.62 Youngs *et al.* (1988)

- Ground-motion model is:

$$\ln(a_{\max}) = C_1 + C_2 M_w - C_3 \ln[R + C_4 \exp(C_5 M_w)] + B Z_t$$

  where $a_{\max}$ is in g, $C_1 = 19.16$, $C_2 = 1.045$, $C_3 = 4.738$, $C_4 = 205.5$, $C_5 = 0.0968$, $B = 0.54$ and $\sigma = 1.55 - 0.125 M_w$.

- Use only rock records to derive equation but use some (389 records) for other parts of study. Classification using published shear-wave velocities for some sites.
- Exclude data from very soft lake deposits such as those in Mexico City because may represent site with special amplification characteristics.
- Data from subduction zones of Alaska, Chile, Peru, Japan, Mexico and Solomon Islands.
- Use two basic types of earthquake:

$Z_t = 0$ Interface earthquakes: low angle, thrust faulting shocks occurring on plate interfaces.

$Z_t = 1$ Intraslab earthquakes: high angle, predominately normal faulting shocks occurring within down going plate.

  Classification by focal mechanisms or focal depths (consider earthquakes with depths $> 50\,\mathrm{km}$ to be intraslab). Note that possible misclassification of some intraslab shocks as interface events because intraslab earthquakes do occur at depths $< 50\,\mathrm{km}$.

- Plots PGA from different magnitude earthquakes against distance; find near-field distance saturation.
- Originally include anelastic decay term $-C_6 R$ but C_6 was negative (and hence nonphysical) so remove.
- Plot residuals from original PGA equation (using rock and soil data) against M_w and R; find no trend with distance but reduction in variance with increasing M_w. Assume standard deviation is a linear function of M_w and find coefficients using combined rock and soil data (because differences in variance estimation from rock and soil are not significant).
- Use derived equation connecting standard deviation and M_w for weighted (weights inversely proportional to variance defined by equation) nonlinear regression in all analyses.

- Plot residuals from original PGA equation; find that hypothesis that coefficients of equations for interface and intraslab earthquakes are the same can be rejected (using likelihood ratio test for nonlinear regression models) at 0.05 percentile level for both soil and rock. Try including a term proportional to depth of rupture into equation (because intraslab deeper than interface events) but find no significant reduction in standard error. Introduce BZ_t term into equation; find B is significant at 0.05 percentile level. Try including rupture type dependence into other coefficients but produces no further decrease in variance so reject.

- Use only data from sites with multiple recordings of both interface and intraslab earthquakes and include dummy variables, one for each site, to remove differences due to systematic site effects. Fix C_1 to C_5 to values from entire set and find individual site terms and B; find B is very similar to that from unconstrained regression.

- Examine residuals for evidence of systematic differences between ground motion from different subduction zones; find no statistically significant differences in PGA among different subduction zones.

- Use geometric mean of two horizontal components to remove effect of component-to-component correlations that affect validity of statistical tests assuming individual components of motion represent independent measurements of ground motion. Results indicate no significant difference between estimates of variance about median relationships obtained using geometric mean and using both components as independent data points.

- Extend to $M_w > 8$ using finite difference simulations of faulting and wave propagation modelled using ray theory. Method and results not reported here.

2.63 Abrahamson & Litehiser (1989)

- Ground-motion model is:

$$\log_{10} a = \alpha + \beta M - \bar{c} \log_{10}[r + \exp(h_2 M)] + F\phi + Ebr$$

  where $F = 1$ for reverse or reverse oblique events and 0 otherwise and $E = 1$ for interplate events and 0 otherwise, a is in g, for horizontal PGA $\alpha = -0.62$, $\beta = 0.177$, $\bar{c} = 0.982$, $h_2 = 0.284$, $\phi = 0.132$, $b = -0.0008$ and $\sigma = 0.277$ and for vertical PGA $\alpha = -1.15$, $\beta = 0.245$, $\bar{c} = 1.096$, $h_2 = 0.256$, $\phi = 0.096$, $b = -0.0011$ and $\sigma = 0.296$.

- Consider three site classifications, based on Joyner & Boore (1981):

  1. Rock: corresponds to C, D & E categories of Campbell (1981), 159 records.
  2. Soil: corresponds to A,B & F categories of Campbell (1981), 324 records.
  3. Unclassified: 102 records.

  Use to examine possible dependence in residuals not in regression because of many unclassified stations.

- Data based on Campbell (1981).

- Fault mechanisms are: strike-slip (256 records from 28 earthquakes), normal (14 records from 7 earthquakes), normal oblique (42 records from 12 earthquakes), reverse (224 records from 21 earthquakes) and reverse oblique (49 records from 8 earthquakes). Grouped into normal-strike-slip and reverse events. Weakly correlated with magnitude (0.23), distance (0.18) and tectonic environment (0.03).
- Tectonic environments are: interplate (555 records from 66 earthquakes) and intraplate (30 records from 10 earthquakes) measurements. Weakly correlated with magnitude (-0.26), distance (-0.17) and fault mechanism (0.03).
- Depths less than $25\,\mathrm{km}$.
- Use array average (37 instruments are in array) from 10 earthquakes recorded at SMART 1 array in Taiwan.
- Most records from distances less than $100\,\mathrm{km}$ and magnitude distribution is reasonably uniform but correlation between magnitude and distance of 0.52.
- Try two-stage technique and model (modified to include fault mechanism and tectonic environment parameters) of Joyner & Boore (1981), find inadmissable positive anelastic coefficient, so do not use it.
- Use a hybrid regression technique based on Joyner & Boore (1981) and Campbell (1981). A method to cope with highly correlated magnitude and distance is required. First step: fit data to $f_2(r) = \bar{c}\log_{10}(r + h)$ and have separate constants for each earthquake (like in two-stage method of Joyner & Boore (1981)). Next holding $\bar{c}$ constant find α, β, b and h_2 from fitting $h = \exp(h_2 M)$. Weighting based on Campbell (1981) is used.
- Form of h chosen using nonparametric function, $H(M)$, which partitions earthquakes into 0.5 unit bins. Plot $H(M)$ against magnitude. Find that $H(M) = h_1 \exp(h_2 M)$ is controlled by Mexico (19/9/1985) earthquake and h_1 and h_2 are highly correlated, 0.99, although does given lower total variance. Choose $H(M) = \exp(h_2 M)$ because Mexico earthquake does not control fit and all parameters are well-determined, magnitude dependent h significant at 90%.
- Try removing records from single-recorded earthquakes and from shallow or soft soil but effect on predictions and variance small ($< 10\%$).
- Plot weighted residuals within $10\,\mathrm{km}$ no significant, at 90%, trends are present.
- Find no significant effects on vertical PGA due to site classification.

2.64 Campbell (1989)

- Ground-motion model is:

$$\ln \mathrm{PHA} = a + bM_L - 1.0 \ln[R + c_1]$$

  where PHA is in g, $a = -2.501$, $b = 0.623$, $c_1 = 7.28$ and $\sigma = 0.506$.
- Selects records from deep soil ($> 10\,\mathrm{m}$). Excludes data from shallow soil ($\leq 10\,\mathrm{m}$) and rock sites and those in basements of buildings or associated with large structures, such as dams and buildings taller than two storeys. Selects records with epicentral distances

$\leq 20\,\text{km}$ for $M_L < 4.75$ and distances $\leq 30\,\text{km}$ for $M_L \geq 4.75$ to minimize regional differences in anelastic attenuation and potential biases associated with nontriggering instruments and unreported PGAs.

- Focal depths, H, between 1.8 and $24.3\,\text{km}$ with mean of $8.5\,\text{km}$.

- PGAs scaled from either actual or uncorrected accelerograms in order to avoid potential bias due to correction.

- Uses weighted nonlinear least squares technique of Campbell (1981).

- Tries two other forms of equation: $\ln \text{PHA} = a + bM_L - 1.0 \ln[R + c_1] + e_1 H$ and $\ln \text{PHA} = a + bM_L - 1.0 \ln[R + c_1] + e_2 \ln H$ for epicentral and hypocentral distance. Allows saturation of PGA for short distances but finds nonsignificant coefficients, at 90%. Also tries distance decay coefficient other than -1.0 but finds instability in analysis.

- Examines normalised weighted residuals against focal depth, M_L and distance. Finds that although residuals seem to be dependent on focal depth there are probably errors in focal depth estimation for deep earthquakes in the study so the dependence may not be real. Finds residuals not dependent on magnitude or distance.

- Uses 171 records ($0.9 \leq R \leq 28.1\,\text{km}$) from 75 earthquakes ($2.5 \leq M_L \leq 5.0$, $0.7 \leq H \leq 24.3\,\text{km}$) excluded from original analysis because they were on shallow soil, rock and/or not free-field, to examine importance of site geology and building size. Considers difference between PGA from records grouped according to instrument location, building size, embedment, and site geology and the predicted PGA using the attenuation equation to find site factors, S. Groups with nonsignificant, at 90%, values of S are grouped together. Finds two categories: embedded alluvial sites from all building sizes (38 records) and shallow-soil (depth of soil $\leq 10\,\text{m}$) sites (35 records) to have statistically significant site factors.

- Performs regression analysis on all records (irrespective of site geology or building size) from Oroville (172 records from 32 earthquakes) and Imperial Valley (71 records from 42 earthquakes) to find individual sites that have significant influence on prediction of PGA (by using individual site coefficients for each station). Finds equations predict similar PGA to those predicted by original equation. Finds significant differences between PGA recorded at different stations in the two regions some related to surface geology but for some finds no reason.

- Uses 27 records ($0.2 \leq R \leq 25.0\,\text{km}$) from 19 earthquakes ($2.5 \leq M_{bLG} \leq 4.8$, $0.1 \leq H \leq 9\,\text{km}$) from E. N. America to examine whether they are significantly different than those from W. N. America. Finds residuals significantly, at 99% level, higher than zero and concludes that it is mainly due to site effects because most are on shallow soils or other site factors influence ground motion. Correcting the recorded PGAs using site factors the difference in PGA between E. N. America and W. N. America is no longer significant although notes may not hold for all of E. N. America.

2.65 Ordaz *et al.* (1989)

- Ground-motion model is unknown.

2.66 Alfaro *et al.* (1990)

- Ground-motion model for near field is:

$$\log(A) = a_1 + a_2 M_s - \log(r^2 + a_3^2)^{\frac{1}{2}}$$

where A is in g, $a_1 = -1.116$, $a_2 = 0.312$, $a_3 = 7.9$ and $\sigma = 0.21$.

Ground-motion model for far field is:

$$\log(A) = b_1 + b_2 M_s + b_3 \log(r^2 + b_4^2)^{\frac{1}{2}}$$

where A is in g, $b_1 = -1.638$, $b_2 = 0.438$, $b_3 = -1.181$, $b_4 = 70.0$ and $\sigma = 0.21$.

- Separate crustal and subduction data because of differences in travel path and stress conditions:

  1. Near field
  2. Far field, 20 records from San Salvador, 20 earthquakes, $4.2 \leq M_s \leq 7.2$, depths between 36 and $94\,\mathrm{km}$, $31 \leq r \leq 298\,\mathrm{km}$.

2.67 Ambraseys (1990)

- Ground-motion model is:

$$\begin{aligned} \log y &= \alpha + \beta M_w - \log r + br \\ \text{where } r &= (d^2 + h^2)^{1/2} \end{aligned}$$

where y is in g, $\alpha = -1.101$, $\beta = 0.2615$, $b = -0.00255$, $h = 7.2$ and $\sigma = 0.25$.

- Uses data and method of Joyner & Boore (1981) but re-evaluates M_w for all earthquakes. Finds some large changes, e.g. Santa Barbara changes from $M_w = 5.1$ to $M_w = 5.85$. Uses M_L for 2 earthquakes ($M_L = 5.2$, 6.2).

- Find effect of uncertainty in M_w causes less than 10% change in σ.

- Also calculates equation using M_s instead of M_w.

- Finds assumption $M_s = M_w$ introduces bias, particularly for small magnitude shocks, on unsafe side, and this can be significant in cases where there is a preponderance of small earthquakes in set.

2.68 Campbell (1990)

- Ground-motion model is:

$$\begin{aligned} \ln(Y) &= a + bM + d\ln[R + c_1 \exp(c_2 M)] + eF + f_1 \tanh[f_2(M + f_3)] \\ &\quad + g_1 \tanh(g_2 D) + h_1 K_1 + h_2 K_2 + h_3 K_3 \end{aligned}$$

where Y is in g, $a = -2.245$, $b = 1.09$, $c_1 = 0.361$, $c_2 = 0.576$, $d = -1.89$, $e = 0.218$, $f_1 = 0$, $f_2 = 0$, $f_3 = 0$, $g_1 = 0$, $g_2 = 0$, $h_1 = -0.137$, $h_2 = -0.403$ and $h_3 = 0$. $\sigma = 0.517$ for $M \leq 6.1$ and $\sigma = 0.387$ for $M \geq 6.2$. Also given is $\sigma = 0.450$ for $M \geq 4.7$.

- Records from firm soil and soft rock sites. Characterises site conditions by depth to basement rock (sediment depth) in km, D.
- Records from different size buildings. $K_1 = 1$ for embedded buildings 3–11 storeys, $K_2 = 1$ for embedded buildings with >11 storeys and $K_3 = 1$ for non-embedded buildings >2 storeys in height. $K_1 = K_2 = K_3 = 0$ otherwise.
- Uses two fault mechanisms:

$F = 0$ Strike-slip

$F = 1$ Reverse

2.69 Dahle *et al.* (1990b) & Dahle *et al.* (1990a)

- Ground-motion model is:

$$\begin{aligned}\ln A &= c_1 + c_2 M + c_4 R + \ln G(R, R_0)\\ \text{where } G(R, R_0) &= R^{-1} \quad \text{for} \quad R \leq R_0\\ \text{and: } G(R, R_0) &= R_0^{-1}\left(\frac{R_0}{R}\right)^{5/6} \quad \text{for} \quad R > R_0\end{aligned}$$

  where A is in $\mathrm{m/s^2}$, $c_1 = -1.471$, $c_2 = 0.849$, $c_4 = -0.00418$ and $\sigma = 0.83$.

- Use records from rock sites (presumably with hard rock or firm ground conditions).
- Assume intraplate refers to area that are tectonically stable and geologically more uniform than plate boundary areas. Select records from several 'reasonably' intraplate areas (eastern N. America, China, Australia, and some parts of Europe), due to lack of data.
- Select records which are available unprocessed and with sufficient information on natural frequency and damping of instrument.
- Use M_s, when available, because reasonably unbiased with respect to source dimensions and there is globally consistent calculation method.
- Most (72%) records from earthquakes with $M \leq 5.5$. Tangshan and Friuli sequence comprise a large subset. Correlation coefficient between magnitude and distance is 0.31.
- Instrument correct records and elliptical filter with pass band 0.25 to $25.0\,\mathrm{Hz}$.
- If depth unknown assume $15\,\mathrm{km}$.
- Choose $R_0 = 100\,\mathrm{km}$ although depends on crustal structure and focal depth. It is distance at which spherical spreading for S waves overtaken by cylindrical spreading for Lg waves.
- PGA attenuation relation is pseudo-acceleration equation for $0.025\,\mathrm{s}$ period and 5% damping.
- Plot residuals against magnitude and distance.
- Note 'first order' results, because data from several geological regions and use limited data base.

2.70 Jacob *et al.* (1990)

- Ground-motion model is:

$$A = 10^{(a_1+a_2M+a_3\log d+a_4d)}$$

  where A is in g, $a_1 = -1.43$, $a_2 = 0.31$, $a_3 = -0.62$ and $a_4 = -0.0026$ (σ not given).

- Note equation only for hard rock sites.

- Equation from a composite of two separate regressions: one using data from 6 earthquakes, $4.7 \leq M \leq 6.4$ and d primarily between 40 and $820\,\mathrm{km}$ and one using the same data supplemented with data from 2 earthquakes with $M = 1.8$ and $M = 3.2$ and $d \leq 20\,\mathrm{km}$ to extend results to smaller M and d. Give no details of this composite regression.

- Note regressions are preliminary and should be tested against more data.

- Note careful assessment of uncertainties is required.

2.71 Sen (1990)

- Ground-motion model is:

$$\ln \mathrm{PGA} = a + bM + c\ln(r + h) + \phi F$$

  where PGA is in $\mathrm{cm/s^2}$, $a = 1.375$, $b = 1.672$, $c = -1.928$ and $\phi = 0.213$ (h not given). Standard deviation is composed of two parts, inter-site $\tau = 0.261$ and intra-site $\sigma = 0.653$. $F = 1$ for thrust mechanism and 0 otherwise.

- Computes theoretical radiation pattern and finds a linear trend between residuals and radiation pattern but does not model.

2.72 Sigbjörnsson (1990)

- Ground-motion model is:

$$a_{\mathrm{peak}} = \alpha_0 \exp(\alpha_1 M)\exp(-\alpha_2 R)R^{-\alpha}P$$

  where $P = 1$.

- Notes that data are very limited and any definite conclusions should, therefore, be avoided.

- Does not give coefficients, only predictions.

2.73 Tsai *et al.* (1990)

- Ground-motion model is:

$$\ln y = C_0 + C_1M + C_2(8.5 - M)^{2.5} + C_3\ln[D + C_4\exp(C_5M)]$$

  where y is in g, $C_3 = -2.1$, $C_4 = 0.616$, $C_5 = 0.524$ and for $M \geq 6.5$ $C_0 = -1.092$, $C_1 = 1.10$, $C_2 = 0$ and $\sigma = 0.36$ and for $M < 6.5$ $C_0 = -0.442$, $C_1 = 1.0$, $C_2 = 0$ and $\sigma = 1.27 - 0.14M$.

- All records from rock or rock-like sites.
- Separate equation for $M < 6.5$ and $M \geq 6.5$.
- Use only shallow crustal thrust earthquakes.
- Use another database of rock and soil site records and simulated acceleration time histories to find conversion factors to predict strike-slip and oblique ground motions from the thrust equation given above. For strike-slip conversion factor is 0.83 and for oblique conversion factor is 0.91.
- Standard deviation, σ, for $M \geq 6.5$ from regression whereas σ for $M < 6.5$ from previous results. Confirm magnitude dependence of standard deviation using 803 recordings from 124 earthquakes, $3.8 \leq M_w \leq 7.4$, $D < 100\,\mathrm{km}$.

2.74 Ambraseys & Bommer (1991) & Ambraseys & Bommer (1992)

- Ground-motion model is:

$$\begin{aligned} \log a &= \alpha + \beta M - \log r + br \\ \text{where } r &= (d^2 + h_0^2)^{1/2} \\ \text{or: } r &= (d^2 + h^2)^{1/2} \end{aligned}$$

  where a is in g, for horizontal PGA $\alpha = -1.09$, $\beta = 0.238$, $b = -0.00050$, $h = 6.0$ and $\sigma = 0.28$ and for vertical PGA $\alpha = -1.34$, $\beta = 0.230$, $b = 0$, $h = 6.0$ and $\sigma = 0.27$. When use focal depth explicitly: for horizontal PGA $\alpha = -0.87$, $\beta = 0.217$, $b = -0.00117$ and $\sigma = 0.26$ and for vertical PGA $\alpha = -1.10$, $\beta = 0.200$, $b = -0.00015$ and $\sigma = 0.26$.

- Consider two site classifications (without regard to depths of deposits) but do not model:
  1. Rock
  2. Alluvium
- Select records which have: $M_s \geq 4.0$ and standard deviation of M_s known and reliable estimates of source-site distance and focal depth, $h \leq 25\,\mathrm{km}$, regardless of local soil conditions from free-field and bases of small buildings. No reliable data or outliers excluded. Records from instruments at further distances from the source than the closest non-triggered instrument were non-excluded because of non-homogeneous and irregularly spaced networks and different and unknown trigger levels.
- Most data, about 70%, with distances less than $40\,\mathrm{km}$. Note strong bias towards smaller values of magnitude and PGA.
- PGA read from analogue and digitised data, with different levels of processing. Differences due to different processing usually below 5%, but some may be larger.
- Errors in distances for small shocks may be large.
- Prefer one-stage technique because second step of two-stage method would ignore records from singly-recorded earthquakes which compose over half the events, also find more realistic, b, and h_0 using one-stage method. Do not use weighting because involves assumptions which are difficult to verify.

- Find inadmissable and positive b for vertical PGA so remove and repeat.
- Remove records from distances less than or equal to half their focal depth and also less than or equal to their focal depth, find that h_0 is governed by near-field data.
- Use focal depth explicitly, by replacing $r = (d^2 + h_0^2)^{1/2}$ by $r = (d^2 + h^2)^{1/2}$. Find lower standard deviation and that it is very significant.
- Repeat analysis on subsets of records grouped by focal depth. Find no correlation between h_0 and focal depth of subset. Use h_0 equal to mean focal depth in each subset and find similar results to when focal depth used explicitly.
- Repeat analysis with geometric attenuation coefficient equal to -0.83, corresponding to the Airy phase, as opposed to -1.0.
- Find small dependence of horizontal PGA on site classification, note due to level of information available.

2.75 Crouse (1991)

- Ground-motion model is:

$$\ln \mathrm{PGA} = p_1 + p_2 M + p_4 \ln[R + p_5 \exp(p_6 M)] + p_7 h$$

  where PGA is in gal, using all PGA values $p_1 = 6.36$, $p_2 = 1.76$, $p_4 = -2.73$, $p_5 = 1.58$, $p_6 = 0.608$, $p_7 = 0.00916$ and $\sigma = 0.773$.
- Use data from stiff soil sites (depth of soil $< 25\,\mathrm{m}$).
- Include data from any zones with strong seismic coupling, such as the younger subduction zones (S.W. Japan, Alaska, C. America (Mexico), C. Chile, Peru and northern Honshu and Kuril subduction zones in Japan) unless compelling reasons to exclude data. Do this because lack of data from Cascadia. Most ($> 70\%$) are from Japan.
- Focal depths, h, between 0 and $238\,\mathrm{km}$.
- Compare Japanese and Cascadia PGA values for earthquakes with similar magnitude and depths and find similar.
- Do not exclude data from buildings or which triggered on S-wave. Note could mean some PGAs are underestimated.
- Plot ground motion amplitude (PGA and also some maximum displacements from seismograms) against distance for a number of large magnitude shocks (including some data from rock sites which not included in set for regression). Find that rate of attenuation becomes smaller for shorter distances and process is magnitude dependent. Also plot Japanese PGA data, from earthquakes with $h \leq 50\,\mathrm{km}$, split into three distance groups (between 50 and $75\,\mathrm{km}$, between 100 and $150\,\mathrm{km}$ and between 250 and $300\,\mathrm{km}$) find as distance increases magnitude scaling becomes larger and possible saturation in PGA for large magnitudes. Fit $\ln \mathrm{PGA} = p_1 + p_2 \ln(R + C)$ to some PGA values from large magnitude shocks for $C = 0$ and $C > 0$, find lower standard deviation for $C > 0$.

- Fit $\ln \mathrm{PGA} = a + bM$ and $\ln \mathrm{PGA} = a + bM + cM^2$ to Japanese data split into the three distance groups (mentioned above); find b increases with increasing distance range but both equations fit data equally well.
- Constrain p_4 to negative value and p_5 and p_6 to positive values.
- Include quadratic magnitude term, $p_3 M^2$, but find equal to zero.
- Plot residuals against M; find uniformly distributed and evidence for smaller residuals for larger M.
- Plot residuals against R[4] and find decreasing residuals for increasing R.
- Give equation using only those records available in digital form (235 records).

2.76 Garcìa-Fernàndez & Canas (1991) & Garcia-Fernandez & Canas (1995)

- Ground-motion model is:

$$\ln \mathrm{PGA} = \ln C_0 + C_1 M - 0.5 \ln r - \gamma r$$

  where PGA is in $\mathrm{cm/s^2}$, for Iberian Peninsula $\ln C_0 = -5.13$, $C_1 = 2.12$ and $\gamma = 0.0039$, for NE region $\ln C_0 = -4.74$, $C_1 = 2.07$ and $\gamma = 0.0110$ and for SSE region $\ln C_0 = -5.30$, $C_1 = 2.21$ and $\gamma = 0.0175$ (σ is not given).

- Derive equations for two regions:

  SSE South south-east part of the Iberian peninsula, from the Guadalquivir basin to the Mediterranean Sea, including the Betic Cordillera, 140 records from 5 stations.

  NE North-east part of the Iberian peninsula, including the Pyrenees, the Catalan Coastal Ranges, the Celtiberian chain and the Ebro basin, 107 records from 3 stations.

- Use vertical-component short-period analogue records of Lg-waves (which are believed to have the largest amplitudes for the period range 0.1 to $1s$) from regional earthquakes in Iberian Peninsula.
- Processing procedure is: digitise seismogram using irregular sampling rate to get better sampling at peaks and 'kinks', select baseline, apply cubic spline interpolation and compare original and digitised seismograms. Next the Fourier amplitude spectrum is computed and the instrument amplitude response is removed.
- Estimate PGA using the maximum value of pseudo-absolute acceleration obtained from Fourier amplitude spectra. Derived equations are for characteristic frequency of $5\,\mathrm{Hz}$.
- Compare estimated PGAs with observed PGAs from five earthquakes and find good agreement.
- Use $5\,\mathrm{Hz}$ γ values from Garcia-Fernandez & Canas (1992) and Vives & Canas (1992).

[4] Not shown in paper.

2.77 Geomatrix Consultants (1991), Sadigh *et al.* (1993) & Sadigh *et al.* (1997)

- Ground-motion model is:

$$\ln \mathrm{PGA} = C_1 + C_2 M + C_3 \ln \left(r_{\mathrm{rup}} + C_4 \mathrm{e}^{C_5 M} \right) + C_6 Z_T$$

  where PGA is in g, for horizontal PGA, rock sites and strike-slip faulting $C_3 = 0$ and $C_4 = -2.100$, for $M \leq 6.5$ $C_1 = -0.624$, $C_2 = 1.0$, $C_5 = 1.29649$ and $C_6 = 0.250$ and for $M > 6.5$, $C_1 = -1.274$, $C_2 = 1.1$, $C_5 = -0.48451$ and $C_6 = 0.524$. For reverse and thrust earthquakes multiply strike-slip prediction by 1.2. $\sigma = 1.39 - 0.14M$ for $M < 7.21$ and $\sigma = 0.38$ for $M \geq 7.21$. For horizontal PGA and deep soil $C_2 = 1.0$, $C_3 = 1.70$ and $C_6 = 0$, for strike-slip faulting $C_1 = -2.17$ and for reverse or thrust faulting $C_1 = -1.92$, for $M \leq 6.5$ $C_4 = 2.1863$ and $C_5 = 0.32$ and for $M > 6.5$ $C_4 = 0.3825$ and $C_5 = 0.5882$. $\sigma = 1.52 - 0.16M$ for $M \leq 7$ and $\sigma = 0.40$ for $M = 7$.

  For vertical PGA, rock sites and strike-slip faulting $C_3 = 0$ and $C_4 = -2.300$, for $M \leq 6.5$ $C_1 = -0.430$, $C_2 = 1.0$, $C_5 = 1.2726$ and $C_6 = 0.228$ and for $M > 6.5$, $C_1 = -1.080$, $C_2 = 1.1$, $C_5 = -0.3524$ and $C_6 = 0.478$. For reverse and thrust earthquakes multiply strike-slip prediction by 1.1 and for oblique faulting multiply by 1.048. $\sigma = 0.48$ for $M \geq 6.5$, $\sigma = 3.08 - 0.40M$ for $6 < M < 6.5$ and $\sigma = 0.68$ for $M \leq 6$.

- Use two site categories (for horizontal motion):

  1. Rock: bedrock within about a metre of surface. Note that many such sites are soft rock with $V_s \leq 750\,\mathrm{m/s}$ and a strong velocity gradient because of near-surface weathering and fracturing, 274 records.
  2. Deep soil: greater than $20\,\mathrm{m}$ of soil over bedrock. Exclude data from very soft soil sites such as those from San Francisco bay mud, 690 records.

  Vertical equations only for rock sites.

- Crustal earthquakes defined as those that occur on faults within upper 20 to $25\,\mathrm{km}$ of continental crust.

- Use source mechanism: RV=reverse (26+2) $\Rightarrow Z_T = 1$ and SS=strike-slip (and some normal) (89+0) $\Rightarrow Z_T = 0$. Classified as RV if rake$> 45°$ and SS if rake$< 45°$. Find peak motions from small number of normal faulting earthquakes not to be significantly different than peak motions from strike-slip events so were including in SS category.

- Records from instruments in instrument shelters near ground surface or in ground floor of small, light structures.

- 4 foreign records (1 from Gazli and 3 from Tabas) supplement Californian records.

- Separate equations for $M_w < 6.5$ and $M_w \geq 6.5$ to account for near-field saturation effects and for rock and deep soil sites.

2.78 Huo & Hu (1991)

- Ground-motion model is (case II):

$$\log y = C_1 + C_2 M - C_4 \log[R + C_5 \exp(C_6 M)]$$

where y is in gal, $C_5 = 0.231$ and $C_6 = 0.626$, for rock $C_1 = 0.894$, $C_2 = 0.563$, $C_4 = 1.523$ and $\sigma = 0.220$ and for soil $C_1 = 1.135$, $C_2 = 0.462$, $C_4 = 1.322$ and $\sigma = 0.243$ (these coefficients are from regression assuming M and R are without error).

- Use two site categories:
  1. Rock
  2. Soil
- Supplement western USA data in large magnitude range with 25 records from 2 foreign earthquakes with magnitudes 7.2 and 7.3.
- Note that there are uncertainties associated with magnitude and distance and these should be considered in derivation of attenuation relations.
- Develop method, based on weighted consistent least-square regression, which minimizes residual error of all random variables not just residuals between predicted and measured ground motion. Method considers ground motion, magnitude and distance to be random variables and also enables inverse of attenuation equation to be used directly.
- Note prediction for $R > 100\,\mathrm{km}$ may be incorrect due to lack of anelastic attenuation term.
- Use both horizontal components to maintain their actual randomness.
- Note most data from moderate magnitude earthquakes and from intermediate distances therefore result possibly unreliable outside this range.
- Use weighted analysis so region of data space with many records are not overemphasized. Use M-R subdivisions of data space: for magnitude $M < 5.5$, $5.5 \leq M \leq 5.9$, $6.0 \leq M \leq 6.4$, $6.5 \leq M \leq 6.9$, $7.0 \leq M \leq 7.5$ and $M > 7.5$ and for distance $R < 3$, $3 \leq R \leq 9.9$, $10 \leq R \leq 29.9$, $30 \leq R \leq 59.9$, $60 \leq R \leq 99.9$, $100 \leq R \leq 300$ and $R > 300\,\mathrm{km}$. Assign equal weight to each subdivision, and any data point in subdivision i containing n_i data has weight $1/n_i$ and then normalise.
- To find C_5 and C_6 use 316 records from 7 earthquakes ($5.6 \leq M \leq 7.2$) to fit $\log Y = \sum_{i=1}^{m} C_{2,i}E_i - C_4 \log[r + \sum_{i=1}^{m} R_{0,i}E_i]$, where $E_i = 1$ for ith earthquake and 0 otherwise. Then fit $R_0 = C_5 \exp(C_6 M)$ to results.
- Also try equations: $\log y = C_1 + C_2 M - C_4 \log[R + C_5]$ (case I) and $\log y = C_1 + C_2 M - C_3 M^2 - C_4 \log[R + C_5 \exp(C_6 M)]$ (case III) for $M \leq M_c$, where impose condition $C_3 = (C_2 - C_4 C_6/\ln 10)/(2M_c)$ so ground motion is completely saturated at $M = M_c$ (assume $M_c = 8.0$).
- Find equations for rock and soil separately and for both combined.

2.79 I.M. Idriss (1991) reported in Idriss (1993)

- Ground-motion model is:

$$\ln(Y) = [\alpha_0 + \exp(\alpha_1 + \alpha_2 M)] + [\beta_0 - \exp(\beta_1 + \beta_2 M)] \ln(R + 20) + aF$$

where Y is in g, $a = 0.2$, for $M \leq 6$ $\alpha_0 = -0.150$, $\alpha_1 = 2.261$, $\alpha_2 = -0.083$, $\beta_0 = 0$, $\beta_1 = 1.602$, $\beta_2 = -0.142$ and $\sigma = 1.39 - 0.14M$ and for $M > 6$ $\alpha_0 = -0.050$, $\alpha_1 = 3.477$, $\alpha_2 = -0.284$, $\beta_0 = 0$, $\beta_1 = 2.475$, $\beta_2 = -0.286$ and for $M < 7\frac{1}{4}$ $\sigma = 1.39 - 0.14M$ and for $M \geq 7\frac{1}{4}$ $\sigma = 0.38$.

- Records from rock sites.
- Uses three fault mechanisms:

  F=0 Strike slip
  F=0.5 Oblique
  F=1 Reverse

- Separate equations for $M \leq 6$ and $M > 6$.
- Examines residuals for PGA. Finds average residual almost zero over entire distance range; trend reasonable up to about $60\,\mathrm{km}$ but beyond $60\,\mathrm{km}$ relationship would underestimate recorded PGA.
- Finds standard deviation to be linear function of magnitude.

2.80 Loh *et al.* (1991)

- Ground-motion model is:

$$a = b_1 \mathrm{e}^{b_2 M} (R + b_4)^{-b_3}$$

  where a is in g, $b_1 = 1.128$, $b_2 = 0.728$, $b_3 = 1.743$, $b_4 = 32\,\mathrm{km}$ and $\sigma = 0.563$ (in terms of $\ln$).

- Use only data from rock sites.
- Focal depths, h, between 0.2 and $97.4\,\mathrm{km}$. Most records from $h < 30\,\mathrm{km}$.
- Also derive equations for PGA using $\log_{10}(a) = b_1 + b_2 M + b_3 \log \sqrt{R^2 + b_5^2}$ and $a = b_1 \mathrm{e}^{b_2 M} (R + b_4 \mathrm{e}^{b_5 M})^{-b_3}$ in order to have diversity in the characterisation of ground motion.
- Use r_{hypo} because no clear fault ruptures identified for Taiwanese earthquakes.
- All data from SMA-1s.
- PGAs between 7.3 and $360.2\,\mathrm{cm/s^2}$.

2.81 Matuschka & Davis (1991)

- Exact functional form unknown but based on those of Campbell (1981), Fukushima & Tanaka (1990) and Abrahamson & Litehiser (1989).
- Use three site classes.
- Develop separate equations for each site class. Only possible for two classes. Therefore, modify equation derived for site class C to obtain coefficients for other two classes.
- Digitization sampling rate of records used is $50\,\mathrm{Hz}$. Most data low-pass filtered at $24.5\,\mathrm{Hz}$.

- Most data high-pass filtered with cut-offs above $0.25\,\mathrm{Hz}$.
- Due to limited data, advise caution when using model.

2.82 Niazi & Bozorgnia (1991)

- Ground-motion model is:

$$\ln Y = a + bM + d\ln[R + c_1 \mathrm{e}^{c_2 M}]$$

  where Y is in g, for horizontal PGA $a = -5.503$, $b = 0.936$, $c_1 = 0.407$, $c_2 = 0.455$, $d = -0.816$ and $\sigma = 0.461$ and for vertical PGA $a = -5.960$, $b = 0.989$, $c_1 = 0.013$, $c_2 = 0.741$, $d = -1.005$ and $\sigma = 0.551$.

- All records from SMART-1 array so essentially identical site conditions and travel paths.
- All records from free-field instruments mounted on $4\,\mathrm{inch}$ ($10\,\mathrm{cm}$) thick concrete base mats, approximately 2 by $3\,\mathrm{feet}$ (60 by $90\,\mathrm{cm}$) across.
- Select earthquakes to cover a broad range of magnitude, distance and azimuth and ensuring thorough coverage of the array. Criteria for selection is: at least 25 stations recorded shock, focal depth $< 30\,\mathrm{km}$, hypocentral distance $< 50\,\mathrm{km}$ except for two large earthquakes from beyond $50\,\mathrm{km}$ to constrain distance dependence.
- Focal depths between 0.2 and $27.2\,\mathrm{km}$ with all but one $\leq 13.9\,\mathrm{km}$.
- Azimuths between $60°$ and $230°$.
- Most records (78%) have magnitudes between 5.9 and 6.5. Note magnitude and distance are not independent (correlation coefficient is 0.6).
- Records have sampling interval of $0.01\,\mathrm{s}$. Processed using trapezoidal band passed filter with corner frequencies 0.07, 0.10, 25.0 and $30.6\,\mathrm{Hz}$.
- Not enough information to use distance to rupture zone.
- Source mechanisms of earthquakes are: 4 normal, 2 reverse, 1 reverse oblique and 1 normal oblique with 4 unknown. Do not model source mechanism dependence because of 4 unknown mechanisms.
- Use weighted regression, give equal weight to recordings from each earthquake within each of 10 distance bins (< 2.5, 2.5–5.0, 5.0–7.5, 7.5–10.0, 10.0–14.1, 14.1–20.0, 20–28.3, 28.3–40.0, 40.0–56.6 and 56.6–$130\,\mathrm{km}$). Do this so earthquakes with smaller number of recordings are not overwhelmed by those with a larger coverage and also to give additional weight to shocks recorded over multiple distance bins. Apply two-stage regression, because of high correlation between magnitude and distance, excluding 3 earthquakes ($M = 3.6, 5.0, 7.8$) with 162 records from first stage to reduce correlation between M and R to 0.1. Also do one-stage regression although do not give coefficients.
- Use mean horizontal component because reduces uncertainty in prediction.

- Examine coefficient of variation for each earthquake using median and normalized standard deviation of recordings in inner ring of array. Find evidence for magnitude dependent uncertainty (large magnitude shocks show less uncertainty). Find that main contribution to scatter is inter-event variations again by examining coefficient of variation; although note may be because using dense array data.
- Examine mean residuals of observations from each earthquake. Find evidence for higher than predicted vertical PGA from reverse faulting earthquakes and lower than predicted vertical PGA from normal faulting earthquakes, although due to lack of information for 4 earthquakes note that difficult to draw any conclusions.
- Examine mean residuals of observations from each station in inner ring. Find mean residuals are relatively small compared with standard deviation of regression so variation between stations is less than variation between earthquakes. Find for some stations some large residuals.

2.83 Rogers *et al.* (1991)

- Ground-motion model is:

$$\log a_p = a_1 + 0.36M - 0.002R + a_2 \log R + a_3 S_1 + a_4 S_1 \log R + a_5 S_5 + a_6 S_5 \log R + a_7 S_6 \log R$$

  where a_p is in g, $a_1 = -1.62$, $a_2 = -1.01$, $a_3 = 0.246$, $a_4 = 0.212$, $a_5 = 0.59$, $a_6 = -0.29$, $a_7 = 0.21$ and $\sigma = 0.29$.

- Use six local site classifications:

  S_1 Holocene

  S_2 Pleistocene soil

  S_3 Soft rock

  S_4 Hard rock

  S_5 Shallow ($< 10\,\mathrm{m}$ depth) soil

  S_6 Soft soil (e.g. bay mud)

- Data from about 800 different stations.
- Note that inclusion of subduction-zone events in analysis may affect results with unmodelled behaviour, particularly with regard to distance scaling although believe use of r_{rup} partially mitigates this problem.
- Firstly compute an equation does not include site coefficients. Conduct regression analysis on site-condition subsets of the residuals using M or $\log R$ as dependent variable. Find several regressions are not statistically significant at the 5% level and/or the predicted effects are small at the independent variable extremes. Find strongest effects and most significant results are for shallow soil sites and soft soil sites although because of the high correlation between M and $\log R$ in the set used it is difficult to construct unbiased models.
- Use a stochastic random-vibration approach to find theoretical equations for estimating PGA that include the effect of local site conditions as distance-dependent terms. Using the results from this analysis construct equation based on the observed PGAs. Try

including terms for S_1, S_2, S_5, S_6 and corresponding $\log R$ terms for each site type but iterate to retain only the significant terms.

- Fix magnitude scaling ($0.36M$) and anelastic attenuation ($0.002R$). Do not try to optimise the fit other than using fixed values similar to those given by the stochastic analysis.
- Note that anelastic coefficient may be too low but it produces an acceptable geometric spreading term.
- Note that because Moho critical reflections can increase amplitudes beyond about $50\,\mathrm{km}$ the effects of anelastic or geometric attenuation may be masked.
- Allowing all the coefficients in the equation to be free produces a smaller magnitude scaling coefficient, a smaller geometric spreading coefficient, and a non-significant anelastic attenuation term.
- Note that data from S_5 and S_6 are sparse.
- Compare estimated PGAs with data from within small magnitude ranges. Find that PGAs from Morgan Hill earthquake are overestimated, which believe is due to the unilateral rupture of this earthquake masking the effect of the local site conditions.

2.84 Stamatovska & Petrovski (1991)

- Ground-motion model is:

$$\mathrm{Acc} = b_1 \exp(b_2 M)(R_h + c)^{b_3}$$

Acc is in $\mathrm{cm/s^2}$, $b_1 = 534.355$, $b_2 = 0.46087$, $b_3 = -1.14459$, $c = 25$ and $\sigma_{\ln \mathrm{Acc}} = 0.72936$.

- Data from 141 different sites, which are considered to have average soil conditions.
- Data from Yugoslavia (23 earthquakes), Italy (45 earthquakes), northern Greece (3 earthquakes), Romania (1 earthquake), Mexico (1 earthquake) and the USA (5 earthquakes). Select earthquakes to have range of magnitudes and focal depths.
- Data processed using standard procedure.
- Conduct Pearson χ^2 and Kolmogorov-Smirnov tests to test acceptability of log-normal assumption using a 5% significance level. Conclude that assumption is justified.
- Note the strong influence of the data used on results and the need to improve it.

2.85 Abrahamson & Youngs (1992)

- Ground-motion model is:

$$\ln y = a + bM + d \ln(r + c) + eF$$

where $a = 0.0586$, $b = 0.696$, $c = 12.0$, $d = -1.858$, $e = 0.205$, $\sigma = 0.399$ (intra-event) and $\tau = 0.201$ (inter-event) (units of y are not given but probably g).

- F is fault type (details not given).
- Develop new algorithm for one-stage maximum-likelihood regression, which is more robust than previous algorithms.

2.86 Ambraseys *et al.* (1992)

- Ground-motion model is:

$$\begin{aligned}\log(a) &= c_1 + c_2 M + c_3 r + c_4 \log r \\ r &= (d^2 + h_0^2)^{\frac{1}{2}}\end{aligned}$$

  where a is in g, $c_1 = -1.038$, $c_2 = 0.220$, $c_3 = -0.00149$, $c_4 = -0.895$, $h_0 = 5.7$ and $\sigma = 0.260$.

- Investigate equations of PML (1982) and PML (1985) using criteria:
  1. Is the chosen data set of earthquake strong-motion records suitable to represent the UK seismic environment?
  2. Are the associated seismological and geophysical parameters used in these reports reliable and consistent?
  3. Is the methodology used to derive attenuation laws and design spectra from the data set reliable?

- Investigate effect of different Ground-motion model, one and two-stage regression technique, record selection technique and recalculation of associated parameters. Find these choice cause large differences in predictions.

- Coefficients given above are for PML (1985) data with recalculated magnitudes and distances and addition of extra records from some earthquakes.

2.87 Kamiyama *et al.* (1992) & Kamiyama (1995)

- Ground-motion model is (note that there is a typographical error in Kamiyama *et al.* (1992); Kamiyama (1995) because r_t has been replaced by r_c in equations):

$$\begin{aligned}\log_{10} a_{\max} &= -1.64 R_0 + b_1 R_1 + b_2 R_2 + c_a + \sum_{i=1}^{N-1} A_i S_i \\ R_0 &= \begin{cases} 0 & \text{for} \quad r \leq r_t \\ \log_{10} r - \log_{10} r_c & \text{for} \quad r > r_t \end{cases} \\ R_1 &= \begin{cases} 0 & \text{for} \quad r \leq r_t \\ 1 & \text{for} \quad r > r_t \end{cases} \\ R_2 &= \begin{cases} 0 & \text{for} \quad r \leq r_t \\ M & \text{for} \quad r > r_t \end{cases}\end{aligned}$$

  where $S_i = 1$ for i station, $S_0 = 0$ otherwise, $a_{\max}$ is in $\mathrm{cm/s^2}$, $b_1 = -1.164$, $b_2 = 0.358$, $c_a = 2.91$, $r_c = 5.3\,\mathrm{km}$ and $\sigma = 0.247$ (A_i given in publications but not reported here due to lack of space).

- Instrument correct records and filter with pass band between 0.24 and $11\,\mathrm{Hz}$.

- Model individual soil conditions at each site as amplification factors, AMP_i, as described by Kamiyama & Yanagisawa (1986).

- Most records are from hypocentral distances between 30 and $200\,\mathrm{km}$.

- Focal depths between 0 and $130\,\mathrm{km}$.
- Models peak ground accelerations independent of magnitude and distance in a fault zone, r_t, where $r_t = r_c 10^{(b_1+b_2M)/1.64}$.
- Constrain decay with distance in far field to -1.64 using results from other studies to avoid problems due to correlation between M and $\log_{10} r$.
- Use trial and error method to find r_c so that resulting values of r_t are consistent with empirical estimates of fault length from past studies.
- Also give expression using shortest distance to fault plane (rupture distance), R, by replacing the expression for $r \leq r_c$ and $r > r_c$ by one expression given by replacing r, hypocentral distance, by $R + r_c$ in expression for $r > r_c$. This gives PGA independent of magnitude at distance $R = 0\,\mathrm{km}$.
- Note that use of r_{hypo} is not necessarily best choice but use it due to simplicity.
- Check residual plots; find no trends so conclude adequate from statistical point of view.

2.88 Sigbjörnsson & Baldvinsson (1992)

- Ground-motion model is:

$$\begin{aligned} \log A &= \alpha + \beta M - \log R + bR \\ \text{with: } R &= \sqrt{d^2 + h^2} \end{aligned}$$

  where A is in g, for average horizontal PGA and $4 < M < 6$ $\alpha = -1.98$, $\beta = 0.365$, $b = -0.0039$ and $\sigma = 0.30$, for larger horizontal PGA and $4 < M < 6$ $\alpha = -1.72$, $\beta = 0.327$, $b = -0.0043$ and $\sigma = 0.30$ and for both horizontal PGAs and $2 < M < 6$ $\alpha = -2.28$, $\beta = 0.386$, $b = 0$ and $\sigma = 0.29$.
- Find that Icelandic data does not fit other published relations.
- Find equation using only records with $M \geq 4.0$, h equal to focal depth and both the horizontal components.
- Find equation using only records with $M \geq 4.0$, h equal to focal depth and larger horizontal component.
- Also repeated with all data. Anelastic coefficient constrained to zero because otherwise positive.
- Also done with h free.
- Note that large earthquakes have $h \approx 10\,\mathrm{km}$ while small events have $h \approx 5\,\mathrm{km}$.

2.89 Silva & Abrahamson (1992)

- Ground-motion model is:

$$\ln \mathrm{pga} = c_1 + 1.2M + c_3 \ln(r + 20) + 0.25F$$

  where pga is in g, $c_1 = -3.27$, $c_3 = -1.79$ and $\sigma_{total} = 0.46$ for deep soil and $c_1 = -3.56$, $c_3 = -1.67$ and $\sigma_{total} = 0.46$ for rock/shallow soil.

- Originally use five site classes (chosen based on site response analyses using broad categories and generic site profiles):

    1. Rock. 66 records
    2. Shallow soil ($< 250\,\mathrm{ft}$. 6 records.)
    3. Intermediate depth soil (250–$1000\,\mathrm{ft}$). 2 records.
    4. Deep soil ($> 1000\,\mathrm{ft}$). 51 records.
    5. Alluvium of unknown depth. 10 records.

  but insufficient records in shallow and intermediate classes to evaluate separately so combine rock and shallow classes and intermediate, deep and unknown depth categories to leave two classes: $< 250\,\mathrm{ft}$ and $> 250\,\mathrm{ft}$.

- Use two faulting mechanisms:

$F = 0$ Strike-slip

$F = 1$ Reverse or oblique

- Process data by: 1) interpolation of uncorrected unevenly sampled records to 400 samples per second; 2) frequency domain low-pass filtering using a causal five-pole Butterworth filter with corner frequencies selected based on visual examination of Fourier amplitude spectrum; 3) removal of instrument response; 4) decimation to 100 or 200 samples per second depending on low-pass filter corner frequencies; and 5) application of time-domain baseline correction, using polynomials of degrees zero to ten depending on integrated displacements, and final high-pass filter chosen based on integrated displacements that is flat at corner frequency and falls off proportional to frequency on either side, which is applied in the time domain twice (forward and backwards) to result in zero phase shift.

- Note that due to limited magnitude range of data, magnitude dependence is not well constrained nor is dependency on mechanism. Hence these coefficients are fixed based on previous studies.

- Plot residuals w.r.t. distance. Find slight increase at 70–$100\,\mathrm{km}$. To test if due to Moho bounce repeat regression assuming functional form that is flat between 70 and $90\,\mathrm{km}$ but this produced a smaller likelihood. Conclude that data does not support significant flattening at $< 100\,\mathrm{km}$.

- Note that model is preliminary.

2.90 Taylor Castillo *et al.* (1992)

- Ground-motion model is:

$$\ln(A) = a_1 + a_2 M_s + a_3 \ln(R) + a_4 R$$

  where A is in $\mathrm{m/s^2}$, $a_1 = 0.339$, $a_2 = 0.455$, $a_3 = -0.67$, $a_4 = -0.00207$ and $\sigma = 0.61$.

2.91 Tento *et al.* (1992)

- Ground-motion model is:

$$\begin{aligned}\ln \mathrm{PGA} &= b_1 + b_2 M + b_3 R - \ln R \\ \text{where } R &= (d^2 + h^2)^{1/2}\end{aligned}$$

  where PGA is in gal, $b_1 = 4.73$, $b_2 = 0.52$, $b_3 = -0.00216$, h is mean focal depth of group into which each earthquake is classified and $\sigma = 0.67$.

- Most records from distances between $10\,\mathrm{km}$ and $40\,\mathrm{km}$.

- Correction technique based on uniform Caltech correction procedure. Most (125) were automatically digitised, rest were manually digitised. Roll-on and cutoff frequencies of Ormsby filter were selected by adopting a record dependent criteria. Cutoff frequencies range between $0.13\,\mathrm{Hz}$ and $1.18\,\mathrm{Hz}$ with a median of $0.38\,\mathrm{Hz}$.

- Records included from analysis were from free-field stations. Excluded those not complete (e.g. started during strong-motion phase). Excluded those with epicentral distances greater than that of first nontriggered station.

- Note relatively small influence of form of equation adopted although two step method seems preferable.

- Note correction procedure plays a relevant role in analysis.

- Note using d instead of R causes greater scatter in data.

- Note moderate underestimation for low magnitude in near field and for high magnitude in far field.

2.92 Theodulidis & Papazachos (1992)

- Ground-motion model is:

$$\ln Y = C_1 + C_2 M + C_3 \ln(R + R_0) + C_4 S$$

  where Y is in $\mathrm{cm/s^2}$, $C_1 = 3.88$, $C_2 = 1.12$, $C_3 = -1.65$, $R_0 = 15$, $C_4 = 0.41$ and $\sigma = 0.71$.

- Use two site categories (mean opinion of seven specialists who classified sites into three categories: soft alluvium, crystalline rock and intermediate):

  S=1 Rock: 34+4 records. Japanese sites have diluvium with depth to bedrock $H < 10\,\mathrm{m}$. Alaskan sites have $\mathrm{PGV/PGA} \approx 66 \pm 7\,\mathrm{cms^{-1}g^{-1}}$.

  S=0 Alluvium: 71+12 records. Japanese sites have diluvium $H > 10\,\mathrm{m}$ or alluvium $H < 10\,\mathrm{m}$, and alluvium with $H < 25\,\mathrm{m}$ as well as soft layers with thickness $< 5\,\mathrm{m}$. Alaskan sites have $\mathrm{PGV/PGA} > 66 \pm 7\,\mathrm{cms^{-1}g^{-1}}$.

- 70% of records from ground level or basement of buildings with two storeys or less. Rest from buildings with up to eight storeys.

- Some (16) Greek records manually digitized and baseline corrected, some (22) Greek records manually digitized and filtered and rest of the Greek records automatically digitized and filtered.
- Due to lack of data for $7.0 < M_s < 7.5$ include shallow subduction data from other regions with similar seismotectonic environments (Japan and Alaska) using criteria i) depth $< 35\,\mathrm{km}$, ii) M_w or M_{JMA} between 7.0 and 7.5, iii) instruments triggered before S-wave, iv) free-field recording, v) surface geology known at station. Note M_s, M_w and M_{JMA} are equivalent between 6.0 and 8.0.
- Focal depths between $0\,\mathrm{km}$ ($13\,\mathrm{km}$) and $18\,\mathrm{km}$ ($31\,\mathrm{km}$).
- Most data from $M_s < 5.5$ and from $R < 50\,\mathrm{km}$.
- Use four step regression procedure. First step use only Greek data from $M_s > 6.0$ ($9 \leq R \leq 128\,\mathrm{km}$, 14 records) for which distances are more reliable (use both hypocentral and epicentral distance find epicentral distance gives smaller standard deviation) to find geometrical coefficient C_{31} and R_0 ignoring soil conditions. Next find constant (C_{12}), magnitude (C_{22}) and soil (C_{42}) coefficients using all data. Next recalculate geometrical (C_{33}) coefficient using only Greek data with $M_s > 6.0$. Finally find constant (C_{14}), magnitude (C_{24}) and soil (C_{44}) coefficients using all the data; final coefficients are C_{14}, C_{24}, C_{33} and C_{44}.
- Plot residuals against M_s and R and find no apparent trends. Find residuals (binned into 0.2 intervals) fit normal distribution.

2.93 Abrahamson & Silva (1993)

- Ground-motion model is:

$$\begin{aligned}\ln \text{pga}_{rock} &= \theta_1 + \theta_2 M + \theta_3 \ln[r + \exp(\theta_4 + \theta_5 M)] + \theta_{11} F_1 \\ \ln \text{pga}_{soil} &= \theta_6 + \theta_7 M + \theta_8 \ln[r + \exp(\theta_9 + \theta_{10})] + \theta_{11} F_1\end{aligned}$$

  where pga is in g, $\theta_1 = -4.364$, $\theta_2 = 1.016$, $\theta_3 = -1.285$, $\theta_4 = -3.34$, $\theta_5 = 0.79$, $\theta_6 = -8.698$, $\theta_7 = 1.654$, $\theta_8 = -1.166$, $\theta_9 = -6.80$, $\theta_{10} = 1.40$, $\theta_{11} = 0.17$, $\sigma = 0.44$, $\tau = 0.00$ (sic) and $\sigma_{total} = 0.44$.
- Originally use five site classes (chosen based on site response analyses using broad categories and generic site profiles):
  1. Rock. 78 records
  2. Shallow soil ($< 250\,\mathrm{ft}$. 25 records.)
  3. Intermediate depth soil (250–$1000\,\mathrm{ft}$). 5 records.
  4. Deep soil ($> 1000\,\mathrm{ft}$). 62 records.
  5. Alluvium of unknown depth. 31 records.

  but insufficient records in shallow and intermediate classes to evaluate separately so combine rock and shallow classes and intermediate, deep and unknown depth categories to leave two classes: $< 250\,\mathrm{ft}$ and $> 250\,\mathrm{ft}$.
- Use two faulting mechanisms:

$F_1 = 0$ Strike-slip or normal

$F_1 = 1$ Reverse

- Based on Silva & Abrahamson (1992) (see Section 2.89.
- Only use Nahanni records for spectral ordinates and not PGA because more representative of eastern US rock than western US rock.

2.94 Boore *et al.* (1993), Boore *et al.* (1997) & Boore (2005)

- Ground-motion model is:

$$\log Y = b_1 + b_2(\mathbf{M} - 6) + b_3(\mathbf{M} - 6)^2 + b_4 r + b_5 \log r + b_6 G_B + b_7 G_C$$
$$\text{where } r = (d^2 + h^2)^{1/2}$$

  where Y is in g, for randomly-oriented horizontal component (or geometrical mean) $b_1 = -0.105$, $b_2 = 0.229$, $b_3 = 0$, $b_4 = 0$, $b_5 = -0.778$, $b_6 = 0.162$, $b_7 = 0.251$, $h = 5.57$ and $\sigma = 0.230$ (for geometrical mean $\sigma = 0.208$) and for larger horizontal component $b_1 = -0.038$, $b_2 = 0.216$, $b_3 = 0$, $b_4 = 0$, $b_5 = -0.777$, $b_6 = 0.158$, $b_7 = 0.254$, $h = 5.48$ and $\sigma = 0.205$.

- Due to an error in Equation (3) of Boore *et al.* (1994a) and Equation (6) of Boore *et al.* (1997) σ_c reported in Boore *et al.* (1994a, 1997) are too large by a factor of $\sqrt{2}$. Therefore correct values of standard deviations are: $\sigma_f = 0.431$, $\sigma_c = 0.160$, $\sigma_r = 0.460$, $\sigma_s = 0.184$ and $\sigma_{\ln Y} = 0.495$.

- Use three site categories:

Class A $V_{s,30} > 750\,\mathrm{m/s}$, some categorised using measured shear-wave velocity, most estimated $\Rightarrow G_B = 0, G_C = 0$, 48 records

Class B $360 < V_{s,30} \leq 750\,\mathrm{m/s}$, some categorised using measured shear-wave velocity, most estimated $\Rightarrow G_B = 1, G_C = 0$, 118 records.

Class C $180 < V_{s,30} \leq 360\,\mathrm{m/s}$,some categorised using measured shear-wave velocity, most estimated $\Rightarrow G_B = 0, G_C = 1$, 105 records.

  where $V_{s,30}$ is average shear-wave velocity to $30\,\mathrm{m}$.

- Define shallow earthquakes as those for which fault rupture lies mainly above a depth of $20\,\mathrm{km}$.
- Peak acceleration scaled directly from accelerograms, in order to avoid bias from sparsely sampled older data.
- Do not use data from structures three storeys or higher, from dam abutments or from base of bridge columns. Do not use data from more than one station with the same site condition within a circle of radius $1\,\mathrm{km}$ (note that this is a somewhat arbitrary choice).
- Exclude records triggered by S wave.
- Do not use data beyond cutoff distance which is defined as equal to lesser of distance to the first record triggered by S wave and closest distance to an operational nontriggered instrument.

- Note that little data beyond $80\,\mathrm{km}$.
- Due to positive values of b_4 when $b_5 = -1$, set b_4 to zero and let b_5 vary.

2.95 Campbell (1993)

- Ground-motion model is:

$$\begin{aligned}\ln(Y) &= \beta_0 + a_1 M + \beta_1 \tanh[a_2(M-4.7)] - \ln(R^2 + [a_3 \exp(a_1 M)]^2)^{1/2} \\ &\quad - (\beta_4 + \beta_5 M)R + a_4 F + [\beta_2 + a_5 \ln(R)]S + \beta_3 \tanh(a_6 D)\end{aligned}$$

  where Y is in g, $\beta_0 = -3.15$, $\beta_1 = 0$, $\beta_2 = 0$, $\beta_3 = 0$, $\beta_4 = 0.0150$, $\beta_5 = -0.000995$, $a_1 = 0.683$, $a_2 = 0.647$, $a_3 = 0.0586$, $a_4 = 0.27$, $a_5 = -0.105$, $a_6 = 0.620$ and $\sigma = 0.50$.

- Uses two site categories:

  S=0 Quaternary deposits (soil).

  S=1 Tertiary or older sedimentary, metamorphic, and igneous deposits (rock).

  Also includes depth to basement rock (km), D.

- Uses two fault mechanisms:

  F=0 Strike-slip.

  F=1 Reverse, reverse-oblique, thrust, and thrust-oblique.

  Recommends use $F = 0.5$ for normal or unknown mechanisms.

- Gives estimates of average minimum depths to top of seismogenic rupture zone.
- Uses stochastic simulation model to find anelastic coefficients β_4 and β_5 because uses only near-source records.
- Uses weighted nonlinear regression method based on Campbell (1981) to control dominance of well-recorded earthquakes.

2.96 Dowrick & Sritharan (1993)

- Ground-motion model is:

$$\begin{aligned}\log y &= \alpha + \beta \mathbf{M} - \log r + br \\ \text{where } r &= (d^2 + h^2)^{1/2}\end{aligned}$$

  Coefficients are unknown.

- Data from earthquakes occurring between 1987 and 1991.

2.97 Gitterman *et al.* (1993)

- Ground-motion model is:

$$\log Y = a + bM - \log\sqrt{r^2 + h^2} - cr$$

where Y is in g, $a = -5.026$, $b = 0.989$, $h = 2.7$ and $c = 0.00443$ (σ not reported).

- Some data from velocity sensors have been used, after differentiation, to increase amount of data at moderate and long distances.

2.98 McVerry *et al.* (1993) & McVerry *et al.* (1995)

- Ground-motion model is (Type A):

$$\log_{10} \mathrm{PGA} = a + bM_w - cr - d\log_{10} r$$

where PGA is in g, $a = -1.434 \pm 0.339$, $b = 0.209 \pm 0.036$, $c = 0.00297 \pm 0.00093$, $d = -0.449 \pm 0.186$ and $\sigma = 0.276$.

- Find that ground motions in previous earthquakes were significantly higher than the motions predicted by equations derived from W. N. America data.
- Only include records from earthquakes for which M_w is known because of poor correlation between M_L and M_w in New Zealand.
- Focal depths, $h_e \leq 122\,\mathrm{km}$.
- 140 records from reverse faulting earthquakes.
- Divide records into crustal and deep earthquakes.
- Only use records for which reliable event information is available, regardless of their distances with respect to untriggered instruments.
- Only use records which triggered on the P-wave.
- Also derive separate equations for shallow, upper crustal earthquakes ($h_e \leq 20\,\mathrm{km}$, 102 records, $5.1 \leq M_w \leq 7.3$, $13 \leq r \leq 274\,\mathrm{km}$) and crustal earthquakes ($h_e \leq 50\,\mathrm{km}$, 169 records, $5.1 \leq M_w \leq 7.3$, $13 \leq r \leq 274\,\mathrm{km}$).
- Also try equations of form: $\log_{10} \mathrm{PGA} = a + bM_w - d\log_{10} r$ (Type B) and $\log_{10} \mathrm{PGA} = a + bM_w - cr - \log_{10} r$ (Type C) because of large standard errors and highly correlated estimates for some of the coefficients (particularly c and d). Find Type B usually gives much reduced standard errors for d than Type A model and have lowest correlation between coefficients, but are sceptical of extrapolating to distance ranges shorter and longer than the range of data. Type C usually has similar standard deviations to Type A. Find that usually all three models give similar predictions over distance range of most of the data, but sometimes considerably different values at other distances.
- Derive separate equations for reverse faulting earthquakes only and usually find similar results to the combined equations.
- Find deep earthquakes produce significantly higher PGAs than shallow earthquakes for similar r.

2.99 Singh *et al.* (1993)

- Ground-motion model is:

$$\begin{aligned}\log(A) &= a_1 + a_2 M + a_3 \log[G(R_0)] + a_4 R_0 \\ \text{where } R_0^2 &= R^2 + (\mathrm{e}^{a_5 M})^2 \\ G(R_0) &= R_0 \text{ for: } R_0 \leq 100\,\mathrm{km} \\ \text{and: } G(R_0) &= \sqrt{(100 R_0)} \text{ for: } R_0 > 100\,\mathrm{km}\end{aligned}$$

  where A is in $\mathrm{cm/s^2}$, $a_1 = 2.74$, $a_2 = 0.212$, $a_3 = -0.99$, $a_4 = -0.000943$, $a_5 = 0.47$ and $\sigma = 0.26$.

- Use same data as Taylor Castillo *et al.* (1992).

- Employ several different regression techniques.

- Select equation found by Bayesian method (given above) for hazard study.

2.100 Steinberg *et al.* (1993)

- Ground-motion model is:

$$\log(A_{\max}) = a_1 M + a_2 \log(D + a_3) + a_4$$

  where $A_{\max}$ is in $\mathrm{cm/s^2}$, $a_1 = 0.54$, $a_2 = -1.5$, $a_3 = 10$ and $a_4 = 1.25$ (σ not reported).

2.101 Sun & Peng (1993)

- Ground-motion model is:

$$\ln A = a + bM - c\ln(R + h) + dT_s$$

  where A is in $\mathrm{cm/s^2}$, $a = 7.7$, $b = 0.49$, $c = 1.45$, $d = 0.19$, $h = 25.0$ and $\sigma = 0.46$.

- Model soil using its fundamental period of the overburden soil, T_s. Thickness of deposit defined as depth to rock base, defined either as $V_s > 800\,\mathrm{m/s}$ or when ratio of shear-wave velocity in ith layer to shear-wave velocity in $i-1$th layer is greater than 2 (only calculate period to $100\,\mathrm{m}$ because only have important effect on structure). For outcropping rock, $T_s = 0.05\,\mathrm{s}$.

- Eight distance intervals used for weighting, five $10\,\mathrm{km}$ wide up to $50\,\mathrm{km}$, 50–$69.9\,\mathrm{km}$, 70–$99.9\,\mathrm{km}$ and 100–$200\,\mathrm{km}$. Within each interval each earthquake received equal weight, inversely proportional to number of records from that earthquake in interval.

- Use resolve accelerations in direction, θ, which gives largest value. Find scatter is lower than for larger horizontal component.

- Many (27) earthquakes only have one record associated with them and 60 records are from San Fernando.

2.102 Ambraseys & Srbulov (1994)

- Ground-motion model is:

$$\begin{aligned}\log a &= b_1 + b_2 M_s + b_3 r + b_4 \log r \\ \text{where } r &= (d^2 + h_0^2)^{0.5}\end{aligned}$$

  where a is in g, $b_1 = -1.58$, $b_2 = 0.260$, $b_3 = -0.00346$, $b_4 = -0.625$, $h_0 = 4$ and $\sigma = 0.26$.

- Do not consider effect of site geology but expect it to be statistically insignificant for PGA.
- Focal depths, $h < 25\,\mathrm{km}$. Mean focal depth is $10 \pm 4\,\mathrm{km}$.
- Mean magnitude of earthquakes considered is 6.0 ± 0.7.
- Most records from $d < 100\,\mathrm{km}$.
- Only use records with $\mathrm{PGA} > 0.01\,\mathrm{g}$.
- Records mainly from SMA-1s located at ground floor or in basements of buildings and structures and free-field sites regardless of topography.
- Records from thrust earthquakes (46% of total), normal earthquakes (26%) and strike-slip earthquakes (28%).
- Baseline correct and low-pass filter records. Select cut-offs from visual examination of Fourier amplitude spectrum of uncorrected time-histories and choose cut-off below which the Fourier amplitude spectrum showed an unrealistic energy increase due to digitization noise and instrument distortions.
- Find (from reprocessing about 300 records) that with very few exceptions differences in PGAs arising from different methods of processing are not significant, remaining below 3%.
- Also derive equation which includes focal depth explicitly.

2.103 Boore *et al.* (1994a) & Boore *et al.* (1997)

- Based on Boore *et al.* (1993) see Section 2.94
- Ground-motion model is:

$$\begin{aligned}\log Y &= b_1 + b_2(\mathbf{M} - 6) + b_3(\mathbf{M} - 6)^2 + b_4 r + b_5 \log r + b_V(\log V_S - \log V_A) \\ \text{where } r &= (d^2 + h^2)^{1/2}\end{aligned}$$

  where Y is in g, b_1 to b_5, h and σ are same as for Boore *et al.* (1993) (see Section 2.94) and for randomly oriented component $b_V = -0.371$ and $V_A = 1400$ and for larger horizontal component $b_V = -0.364$ and $V_A = 1390$.

- Model site effect as a continuous function of average shear-wave velocity to $30\,\mathrm{m}$ deep, V_S.

- Coefficients b_1, b_2, b_3,b_4 and b_5 from Boore *et al.* (1993).
- Find no basis for different magnitude scaling at different distances.
- Find evidence for magnitude dependent uncertainty.
- Find evidence for amplitude dependent uncertainty.
- Find marginal statistical significance for a difference between strike-slip (defined as those with a rake angle within $30°$ of horizontal) and reverse-slip motions but do not model it. Modelled in Boore *et al.* (1994b) (by replacing b_1 by $b_{SS}G_{SS} + b_{RS}G_{RS}$ where $G_{SS} = 1$ for strike-slip shocks and 0 otherwise and $G_{RS} = 1$ for reverse-slip shocks and 0 otherwise) and reported in Boore *et al.* (1997). Coefficients for randomly oriented horizontal component are: $b_{SS} = -0.136$ and $b_{RS} = -0.051$[5].
- Analysis done using one and two-stage maximum likelihood methods; note that results are very similar.
- Earthquakes with magnitudes below 6.0 are poorly represented.
- Note that few Class A records.
- Note that V_S does not model all the effects of site because it does not model effect of the thickness of attenuating material on motion.
- Note that ideally would like to model site in terms of average shear-wave velocity to one-quarter wavelength.
- Note lack measurements from distances greater than $100\,\mathrm{km}$ so that weak-motion data from seismographic stations maybe should be used.
- Note that use of cutoff distances independent of geology or azimuth may be over strict but it is simple and objective. Note that methods based on data from nontriggered stations or using seismogram data may be better.

2.104 El Hassan (1994)

- Ground-motion model is:

$$\log a = C_1 + C_2 M + C_3 \log(R + C_4)$$

  where a is in $\mathrm{cm/s^2}$, $C_1 = 8.65$, $C_2 = 0.71$, $C_3 = -1.6$, $C_4 = 40$ and $\sigma = 0.6$.

- May not be an empirical GMPE but derived through a intensity-PGA relations.

[5]These are taken from Table 8 of Boore *et al.* (1997) which uses natural logarithms so they were converted into terms of logarithms to base 10.

2.105 Fukushima *et al.* (1994) & Fukushima *et al.* (1995)

- Ground-motion model is:

$$\log Y = aM + bX - \log X + \sum \delta_i c_i$$

where Y is in $\mathrm{cm/s^2}$, $\delta_i = 1$ at ith receiver and 0 otherwise, for horizontal PGA $a = 0.918$ and $b = -0.00846$ (σ not given) and for vertical PGA $a = 0.865$ and $b = -0.00741$ (σ not given). c_i given in paper but are not reported here due to lack of space.

- Data from three vertical arrays in Japan so predictions at surface and at different depths down to $950\,\mathrm{m}$.
- Different definition of M_{JMA} for focal depths $> 60\,\mathrm{km}$ so exclude such data. Focal depths between 2 and $60\,\mathrm{km}$.
- Exclude data from earthquakes $M < 5.0$ because errors are larger for smaller events.
- Exclude data for which predicted, using a previous attenuation relation, $\mathrm{PGV} < 0.1\,\mathrm{cm/s}$ in order to find precise attenuation rate.
- Most data from earthquakes with $M \leq 6.0$ and most from $X \leq 100\,\mathrm{km}$.
- Records low-pass filtered with cutoff frequency $25\,\mathrm{Hz}$ for records from 2 sites and $30\,\mathrm{Hz}$ for records from 1 site.
- Use two-stage method because positive correlation between M and X. Also apply one step; find it is biased and two-stage method is most effective method to correct bias.
- Check residuals (not shown) against M and X find no remarkable bias.

2.106 Lawson & Krawinkler (1994)

- Ground-motion model is:

$$\log Y = a + b(M-6) + c(M-6)^2 + d\sqrt{R^2+h^2} + e\log\sqrt{R^2+h^2} + fS_B + gS_C$$

- Use three site categories:
  - A Firm to hard rock: granite, igneous rocks, sandstones and shales with close to widely spaced fractures, $750 \leq V_{s,30} \leq 1400\,\mathrm{m/s} \Rightarrow S_B = 0$, $S_C = 0$.
  - B Gravelly soils and soft to firm rocks: soft igneous rocks, sandstones and shales, gravels and soils with $> 20\%$ gravel, $360 \leq V_{s,30} \leq 750\,\mathrm{m/s} \Rightarrow S_B = 1$, $S_C = 0$.
  - C Stiff clays and sandy soils: loose to very dense sands, silt loams and sandy clays, and medium stiff to hard clay and silty clays ($N > 5\,\mathrm{blows/ft}$), $180 \leq V_{s,30} \leq 360\,\mathrm{m/s} \Rightarrow S_B = 0$, $S_C = 1$.
- For shallow (fault rupture within $20\,\mathrm{km}$ of earth surface) crustal earthquakes.
- Use free-field records. Records not significantly contaminated by structural feedback, excludes records from structures with $>$2 stories.
- Chooses Ground-motion model because of simplicity. Note that other possible forms of equation may have significant effect on results, but including more terms complicates relationships without reducing variability.
- Do not give coefficients only predictions.

2.107 Lungu *et al.* (1994)

- Ground-motion model is:

$$\ln \mathrm{PGA} = c_1 + c_2 M_w + c_3 \ln R + c_4 h$$

where PGA is in g, $c_1 = -2.122$, $c_2 = 1.885$, $c_3 = -1.011$, $c_4 = -0.012$ and $\sigma = 0.502$.

- Focal depth, h, between 79 and 131 km.
- Consider to separate areas of $90°$ to investigate variation with respect to azimuth; find azimuthal dependence.
- Find individual attenuation equations for three earthquakes. Note faster attenuation for smaller magnitude and faster attenuation for deeper events.

2.108 Musson *et al.* (1994)

- Ground-motion model is (model 1):

$$\ln A = a + bM - \ln(R) + dR$$

where A is in $\mathrm{cm/s^2}$, $a = 2.11$, $b = 1.23$ and $d = -0.014$.

Ground-motion model is (model 2):

$$\begin{aligned} \ln A &= c_1 + c_2 M + c_4 R + \ln G(R, R_0) \\ \text{where } G(R, R_0) &= R^{-1} \quad \text{for} \quad R \leq R_0 \\ \text{and: } G(R, R_0) &= R_0^{-1} \frac{R_0}{R}^{5/6} \quad \text{for} \quad R > R_0 \end{aligned}$$

where A is in $\mathrm{m/s^2}$, c_1 and c_2 are from Dahle *et al.* (1990b), $c_4 = -0.0148$ and σ is recommended as 0.65 (although this is from an earlier study and is not calculated in regression).

- Use data from Canada (Saguenay earthquake and Nahanni sequence) and Belgium (Roermond earthquake).
- Focal depths, h, between 1 and 30 km with average 14.4 km.
- Assume peak ground acceleration equals pseudo-acceleration at 30 Hz due to few unclipped horizontal UK records and because instrument response of UK instruments means records unreliable above 30 Hz. Use only digital VME records for 30 Hz model.
- Note poorness of data due to UK data and other data being widely separated thus preventing a comparison between the two sets. Also means straightforward regression methods would be inadequate as there would be little control on shape of curves derived.
- Note earlier models over predict UK data.
- Use two-stage least squares method to give model 1. First stage fit only UK/Belgian data to find b, in second stage use this value of b and use all data to find a and d.

- Do not recommend model 1 for general use because too influenced by limitations of data to be considered reliable. Canadian data probably insufficient to anchor curves at small R/large M and extremely high Saguenay earthquake records carry undue weight.
- Use model of Dahle *et al.* (1990b) to get model 2. Fix c_1 and c_2 to those of Dahle *et al.* (1990b) and find c_4. Prefer this model.

2.109 Radu *et al.* (1994), Lungu *et al.* (1995a) & Lungu *et al.* (1996)

- Ground-motion model is:

$$\ln \mathrm{PGA} = c_1 + c_2 M + c_3 \ln R + c_4 h$$

where PGA is in $\mathrm{cm/s^2}$, $c_1 = 5.432$, $c_2 = 1.035$, $c_3 = -1.358$, $c_4 = -0.0072$ and $\sigma = 0.397$.

- Sites have different soil conditions, some medium and stiff sites and some very soft soil sites.
- Use some records from Moldova and Bulgaria.
- Focal depths, h, between 91 and $133\,\mathrm{km}$.
- Records from free-field or from basements of buildings.
- Originally include data from a shallower (focal depth $79\,\mathrm{km}$), smaller magnitude ($M_L = 6.1$, $M_w = 6.3$) earthquake with shorter return period than other three earthquakes, but exclude in final analysis.
- Originally do attenuation analysis for two orthogonal directions N45E (which is in direction of fault plane) and N35E (which is normal to fault plane). From this define 3 $90°$ circular sectors based roughly on tectonic regions, and calculate attenuation relations for each of these sectors as well as for all data. Find azimuthal dependence.
- Remove 1 to 3 anomalous records per sector.
- Remove the only record from the 4/3/1977 earthquake, because it has a strong influence on results, and repeat analysis using model $\ln \mathrm{PGA} = b_1 + b_2 M + b_3 \ln R$, find lower predicted PGA.
- Find slower attenuation in direction of fault plane compared with normal to fault plane.
- Find faster attenuation and larger standard deviation (by finding attenuation equations for two different earthquakes) for deeper focus and larger magnitude shocks.

2.110 Ramazi & Schenk (1994)

- Ground-motion model is:

$$\begin{aligned} a_h &= a_1 (a_2 + d + H)^{a_5} \exp(a_6 M_s) \\ H &= |d - a_3|^{a_4} \end{aligned}$$

where for horizontal peak acceleration a_h is in $\mathrm{cm/s^2}$, $a_1 = 4000$, $a_2 = 20$, $a_3 = 16$ and $a_4 = 0.63$ for soil sites $a_5 = -2.02$ and $a_6 = 0.8$ and for rock sites $a_5 = -2.11$ and $a_6 = 0.79$ (σ not given). For vertical peak acceleration on soil sites a_v is in $\mathrm{cm/s^2}$ a_1 to a_3 are same as horizontal and $a_4 = 0.48$, $a_5 = -1.75$ and $a_6 = 0.53$ (σ not given).

- Use two site categories (from original of four) for which derive two separate equations:
  1. Rock: mainly category (2) a) loose igneous rocks (tuffs), friable sedimentary rocks, foliated metamorphic rock and rocks which have been loosened by weathering, b) conglomerate beds, compacted sand and gravel and stiff clay (argillite) beds where soil thickness $> 60\,\mathrm{m}$ from bed rock. 29 records.
  2. Soil: mainly category (4) a) soft and wet deposits resulting from high level of water table, b) gravel and sand beds with weak cementation and/or uncementated unindurated clay (clay stone) where soil thickness $> 10\,\mathrm{m}$ from bed rock. 54 records.
- Focal depths between 10 and $69\,\mathrm{km}$.
- Find equations using hypocentral distance but find that poor fit for Rudbar (Manjil) earthquake ($M_s = 7.7$) which conclude due to use of hypocentral rather than rupture distance.
- Find equations using rupture distance[6] for Rudbar (Manjil) earthquake and hypocentral distances for other earthquakes. Coefficients given above. They conclude that it is important that equations are derived using rupture distance rather than hypocentral distance because most destructive earthquakes rupture surface in Iran.
- Do not know physical meaning of H term but find that it causes curves to fit data better.

2.111 Xiang & Gao (1994)

- Ground-motion model is:

$$A_p = a\mathrm{e}^{bM_s}(R + \Delta)^c$$

  where A_p is in $\mathrm{cm/s^2}$ and for combined Yunnan and W. N. American data $a = 1291.07$, $b = 0.5275$, $c = -1.5785$, $\Delta = 15$ and $\sigma = 0.5203$ (in terms of natural logarithm).
- All records from basement rock.
- Most Yunnan data from main and aftershocks of Luquan and Luncang-Gengma earthquakes.
- Records from Lancang-Gengma sequence corrected.
- Most Yunnan records with $3 \leq M_s \leq 5$ and $10 \leq R \leq 40\,\mathrm{km}$.
- To overcome difficulty due to shortage of large magnitude records and sample heterogeneous distribution in near and far fields use W. N. America data, because intensity attenuation is similar.
- Fit curves to Yunnan and Yunnan with W. N. American data. Find curve for combined data has lower variance and fit to observation data for large magnitudes is better (by plotting predicted and observed PGA).

[6] They state it is ‘ . . . closest distance from the exposure of ruptured part of the fault . . . ’ so may not be rupture distance.

2.112 Aman *et al.* (1995)

- Ground-motion model is:

$$\log(a^{1/M}) = b_1 - b_3 \log(R)$$

  where a is in $\mathrm{cm/s^2}$, $b_1 = 0.433$, $b_3 = 0.073$ and $\sigma = 0.037$.

- Data from three earthquakes with M_B of 5.7, one of M_B of 5.8 and the other M_B of 7.2.

- Compare predicted and observed ground motions for 20/10/1991 Uttarkashi earthquake ($M6.1$) and find good fit.

2.113 Ambraseys (1995)

- Ground-motion model is:

$$\begin{aligned} \log a &= A + BM_s + Cr + D\log r \\ \text{where } r^2 &= d^2 + h_0^2 \end{aligned}$$

  where a is in g, for $4.0 \leq M \leq 7.4$: for horizontal PGA not including focal depth $A = -1.43$, $B = 0.245$, $C = -0.0010$, $D = -0.786$, $h_0 = 2.7$ and $\sigma = 0.24$, for vertical PGA not including focal depth $A = -1.72$, $B = 0.243$, $C = -0.00174$, $D = -0.750$, $h_0 = 1.9$ and $\sigma = 0.24$, for horizontal PGA including focal depth $A = -1.06$, $B = 0.245$, $C = -0.00045$, $D = -1.016$, $h_0 = h$ and $\sigma = 0.25$ and for vertical PGA including focal depth $A = -1.33$, $B = 0.248$, $C = -0.00110$, $D = -1.000$, $h_0 = h$ and $\sigma = 0.25$.

- Reviews and re-evaluates distances, focal depths, magnitudes and PGAs because data from variety of sources with different accuracy and reliability. For $M_s > 6.0$ distances have acceptable accuracy but for $M_s < 6.0$ distance, depths and magnitudes are poorly known. Errors in locations for $M_s < 6.0$ still large with no foreseeable means of improving them. Use of r_{epi} for $M_s < 6.0$ justified because difference between r_{jb} and r_{epi} for small earthquakes is not larger than uncertainty in epicentre. Check and redetermine station locations; find large differences in excess of $15\,\mathrm{km}$ for some stations.

- Focal depths poorly determined. Revises 180 depths using S-start times (time between P and S-wave arrival).

- Focal depths $h < 26\,\mathrm{km}$; most (60%+) between 4 and $14\,\mathrm{km}$.

- Does not use M_L because no M_L values for Algeria, Iran, Pakistan, Turkey and former USSR and unreliable for other regions. Does not use magnitude calculated from strong-motion records because magnitude calculation requires point source approximation to be valid. Conversion from M_L to M_s should not be done because of uncertainty in conversion which should be retained.

- Notes that M_s results in nonlinear scaling on PGA with M_w due to nonlinear relationship between $\log M_0$ and M_s.

- Uses PGAs in four forms: maximum values from accelerograms read by others (34%), from corrected records (30%), scaled directly from accelerograms (13%) and from digitised plots (23%). Notes potential bias in using both corrected and uncorrected PGAs but neglects it because small difference ($\lesssim 4\%$ for those checked). Excludes PGAs near trigger level because processing errors can be large. Some unfiltered digital records which require additional processing to simulate SMA-1 could be associated with larger differences ($\lesssim 10\%$).

- Excludes records from basements and ground floors of structures with more than 3 levels. Retains the few records from dam abutments and tunnel portals.
- Excludes records generated by close small magnitude earthquakes triggered by S-wave.
- Does not exclude records obtained at distances greater than shortest distance to an operational but not triggered instrument because of non-constant or unknown trigger levels and possible malfunctions of instruments.
- Uses weighted regression of Joyner & Boore (1988) for second stage.
- Splits data into five magnitude dependent subsets: $2.0 \leq M_s \leq 7.3$ (1260 records from 619 shocks), $3.0 \leq M_s \leq 7.3$ (1189 records from 561 shocks), $4.0 \leq M_s \leq 7.3$ (830 records from 334 shocks), , $5.0 \leq M_s \leq 7.3$ (434 records from 107 shocks), and $3.0 \leq M_s \leq 6.0$ (976 records from 524 shocks). Calculates coefficients for each subset. Finds only small differences $\pm 15\%$ over distance range 1–$200\,\mathrm{km}$ between predictions and uncertainties. Concludes results stable. Prefers results from subset with $4.0 \leq M_s \leq 7.3$.
- Finds it difficult to obtain some vertical accelerations due to low ground motion so ignores data from $> 100\,\mathrm{km}$ with PGA $< 1\%\mathrm{g}$ ($0.1\,\mathrm{m/s^2}$).
- Repeats regression using $r^2 = d^2 + h^2$. Finds depth important.
- Calculates using one-stage method; finds very similar results for $10 < d < 100\,\mathrm{km}$.
- Considers magnitude dependent function: $\log a = b_1 + b_2 M_s + b_3 r + b_4 [r + b_5 \exp(b_6 M_s)]$. Finds b_5 is zero so drops b_3 and repeats. Finds b_5 close to zero so magnitude dependent function not valid for this dataset.
- Local shear-wave velocity, V_s, profiles known for 44 stations (268 records from 132 earthquakes between 2.5 and 7.2) although only 14 from $> 40\,\mathrm{km}$ so barely sufficient to derive equation. Use 145 records from 50 earthquakes with $M_s > 4.0$ to fit $\log a = A + BM_s + Cr + D\log r + E\log V_{s30}$, where V_{s30} is average shear-wave velocity to reference depth of $30\,\mathrm{m}$. Finds C positive so constrain to zero. Find no reduction in standard deviation.
- Uses residuals from main equation to find E. Notes that should not be used because of small number of records. Considers different choices of reference depth; finds using between 5 and $10\,\mathrm{m}$ leads to higher predicted amplifications. Notes better to use V_{s30} because no need for subjective selection of categories.

2.114 Dahle *et al.* (1995)

- Ground-motion model is:

$$\begin{aligned} \ln A &= c_1 + c_2 M_w + c_3 \ln R + c_4 R + c_5 S \\ \text{with: } R &= \sqrt{r^2 + r_h^2} \end{aligned}$$

where A is in $\mathrm{m/s^2}$, $c_1 = -1.579$, $c_2 = 0.554$, $c_3 = -0.560$, $c_4 = -0.0032$, $c_5 = 0.326$, $r_h = 6$ and $\sigma = 0.3535$

- Use records from Costa Rica, Mexico, Nicaragua and El Salvador. Only Mexican earthquakes with $M_w \geq 6.5$ were used.
- Use two site categories:

$S = 0$ Rock: 92 records

$S = 1$ Soil: 88 records

- Use a Bayesian one-stage regression method (Ordaz *et al.* , 1994) to yield physically possible coefficients.
- Consider tectonic type: subduction or shallow crustal but do not model.
- Find no significant difference between Guerrero (Mexico) and other data.
- Find no significant difference between subduction and shallow crustal data.

2.115 Lee *et al.* (1995)

- Ground-motion models are (if define site in terms of local geological site classification):

$$\log a_{\max} = M + \mathrm{Att}(\Delta/L, M, T) + b_1 M + b_2 s + b_3 v + b_4 + b_5 M^2 + \sum_i b_6^i S_L^i + b_{70} r R + b_{71}(1-r)R$$

or (if define site in terms of depth of sediment):

$$\log a_{\max} = M + \mathrm{Att}(\Delta/L, M, T) + b_1 M + b_2 h + b_3 v + b_4 + b_5 M^2 + \sum_i b_6^i S_L^i + b_{70} r R + b_{71}(1-r)R$$

where:

$$\begin{aligned}
\mathrm{Att}(\Delta, M, T) &= \begin{cases} b_0 \log_{10} \Delta & \text{for} \quad R \leq R_{\max} \\ b_0 \log_{10} \Delta_{\max} - (R - R_{\max})/200 & \text{for} \quad R > R_{\max} \end{cases} \\
\Delta &= S \left(\ln \frac{R^2 + H^2 + S^2}{R^2 + H^2 + S_0^2} \right)^{-1/2} \\
\Delta_{\max} &= \Delta(R_{\max}, H, S) \\
R_{\max} &= \frac{1}{2}(-\beta + \sqrt{\beta^2 - 4H^2})
\end{aligned}$$

S_0 is correlation radius of source function and can be approximated by $S_0 \sim \beta T/2$ (for PGA assume $T \approx 0.1\,\mathrm{s}$ so use $S_0 = 0.1\,\mathrm{km}$), β is shear-wave velocity in source region, T is period, S is 'source dimension' approximated by $S = 0.2$ for $M < 3$ and $S = -25.34 + 8.51M$ for $3 \leq M \leq 7.25$, L is rupture length of earthquake approximated by $L = 0.01 \times 10^{0.5M}\ \mathrm{km}$ and v is component direction ($v = 0$ for horizontal 1 for vertical). Different b_0, b_{70} and b_{71} are calculated for five different path categories. Coefficients are not reported here due to lack of space.

- Use four types of site parameter:
  - Local geological site classification (defined for all records):

$s = 0$ Sites on sediments.
$s = 1$ Intermediate sites.
$s = 2$ Sites on basement rock.

- Depth of sediments from surface to geological basement rock beneath site, h (defined for 1675 records out of 1926).
- Local soil type parameter describes average soil stiffness in top 100–$200\,\mathrm{m}$ (defined for 1456 records out of 1926):

$s_L = 0$ 'Rock' soil sites $\Rightarrow S_L^1 = 1$, $S_L^2 = 0$ and $S_L^3 = 0$. Characterises soil up to depth of less than $10\,\mathrm{m}$.
$s_L = 1$ Stiff soil sites $\Rightarrow S_L^1 = 1$, $S_L^2 = 0$ and $S_L^3 = 0$ (shear-wave velocities $< 800\,\mathrm{m/s}$ up to depth of 75–$100\,\mathrm{m}$).
$s_L = 2$ Deep soil sites $\Rightarrow S_L^2 = 1$, $S_L^1 = 0$ and $S_L^3 = 0$. (shear-wave velocities $< 800\,\mathrm{m/s}$ up to depth of 150–$200\,\mathrm{m}$).
$s_L = 3$ Deep cohesionless soil sites $\Rightarrow S_L^3 = 1$, $S_L^1 = 0$ and $S_L^2 = 0$ (only use for one site with 10 records).

- Average soil velocity in top $30\,\mathrm{m}$, v_L (if unavailable then use soil velocity parameter, s_T) (defined for 1572 records out of 1926):

Soil type A $v_L > 750\,\mathrm{m/s}$.
Soil type B $360\,\mathrm{m/s} < v_L \leq 750\,\mathrm{m/s}$.
Soil type C $180\,\mathrm{m/s} < v_L \leq 360\,\mathrm{m/s}$.
Soil type D $v_L \leq 180\,\mathrm{m/s}$.

- Only include records for which significant subset of site parameters (s, h, s_L, v_L) exist.
- Almost all earthquakes have focal depths $H \leq 15\,\mathrm{km}$; all focal depths $H \leq 43\,\mathrm{km}$.
- Use records from 138 aftershocks of Imperial Valley earthquake (15/10/1979), which contribute most of $M \leq 3$ records.
- Use records from 109 earthquakes with $M \leq 3$.
- Use free-field records.
- Characterise path by two methods:
  - Fraction of wave path travelled through geological basement rock measured at surface, from epicentre to station, $0 \leq r \leq 1$.
  - Generalised path type classification:
    1. Sediments to sediments.
    2. Rock-to-sediments, vertically.
    3. Rock-to-sediments, horizontally.
    4. Rock-to-rock.
    5. Rock-to-rock through sediments, vertically.
    6. Rock-to-sediments through rock and sediments, vertically.
    7. Rock-to-sediments though rock and sediments, horizontally.
    8. Rock-to-rock through sediments, horizontally.

Due to lack of data combine path types 2 and 6 in new category 2', combine path types 3 and 7 in new category 3', combine path types 4, 5 and 8 in new category 4' (when $r \neq 1$) and combine 4, 5 and 8 in new category 5' (when $r = 1$).

- Plot PGA against magnitude and distance to get surface by interpolation. Plot without smoothing and with light and intense smoothing. Find for small magnitude ($M \approx 3$–4) earthquakes attenuation is faster than for large magnitude ($M \approx 6$–7) earthquakes.

- Use a multi-step residue regression method. First fit $\log a_{\max} = M + \mathrm{Att}(\Delta, M, T) + b_1 M + b_2 s + b_3 v + b_4 + b_5 M^2$ (or $\log a_{\max} = M + \mathrm{Att}(\Delta, M, T) + b_1 M + b_2 h + b_3 v + b_4 + b_5 M^2$) and calculate residuals $\epsilon = \log a_{\max} - \log \hat{a}_{\max}$ where $a_{\max}$ is estimated PGA and $\hat{a}_{\max}$ is recorded PGA. Fit $\epsilon = b_7^{(-1)} S_L^{(-1)} + b_7^{(0)} S_L^{(0)} + b_7^{(1)} S_L^{(1)} + b_7^{(2)} S_L^{(2)} + b_7^{(3)} S_L^{(3)}$ where $S_L^{(i)} = 1$ if $s_L = i$ and $S_L^{(i)} = 0$ otherwise. Find significant dependence. Try including v_L both as a continuous and discrete parameter in model but not significant at 5% significance level. Next calculate residuals from last stage and fit $\epsilon = b'_0 \log_{10}(\Delta/L) + b'_4 + b_{60} r R + b_{61}(1 - r)R$ for each of the five path type groups (1' to 5'). Lastly combine all the individual results together into final equation.

- Note that b_{70} and b_{71} can only be applied for $R \lesssim 100\,\mathrm{km}$ where data is currently available. For $R \gtrsim 100\,\mathrm{km}$ the predominant wave type changes to surface waves and so b_{70} and b_{71} do not apply.

2.116 Lungu *et al.* (1995b)

- Study almost identical to Radu *et al.* (1994), see Section 2.109, but different coefficients given: $c_1 = 3.672$, $c_2 = 1.318$, $c_3 = -1.349$, $c_4 = -0.0093$ and $\sigma = 0.395$.

2.117 Molas & Yamazaki (1995)

- Ground-motion model is:

$$\log y = b_0 + b_1 M + b_2 r + b_3 \log r + b_4 h + c_i$$

where y is in $\mathrm{cm/s^2}$, $b_0 = 0.206$, $b_1 = 0.477$, $b_2 = -0.00144$, $b_3 = -1$, $b_4 = 0.00311$, $\sigma = 0.276$ and c_i is site coefficient for site i (use 76 sites), given in paper but are not reported here due to lack of space.

- Records from accelerometers on small foundations detached from structures; thus consider as free-field.

- Exclude records with one horizontal component with $\mathrm{PGA} < 1\,\mathrm{cm/s^2}[0.01\,\mathrm{m/s^2}]$ because weaker records not reliable due to resolution ($\pm 0.03\,\mathrm{cm/s^2}[0.0003\,\mathrm{m/s^2}]$) of instruments.

- Exclude earthquakes with focal depths equal to $0\,\mathrm{km}$ or greater than $200\,\mathrm{km}$, due to lack of such data. Depths (depth of point on fault plane closest to site), h, between about $1\,\mathrm{km}$ to $200\,\mathrm{km}$.

- Apply a low-cut filter with cosine-shaped transition from 0.01 to $0.05\,\mathrm{Hz}$.

- Positive correlation between magnitude and distance so use two-stage method.

- Note different definition for M_{JMA} for focal depths $> 60\,\mathrm{km}$.
- Firstly do preliminary analysis with $b_4 = 0$ and no site coefficients; find b_2 is positive so constrain to 0 but find $b_3 < -1.0$ so constrain b_3 to -1.0 and unconstrain b_2. Find linear dependence in residuals on h especially for $h < 100\,\mathrm{km}$. Find significant improvement in coefficient of determination, R^2, using terms $b_4 h$ and c.
- Find singularity in matrices if apply two-stage method, due to number of coefficients, so propose a iterative partial regression method.
- Also separate data into five depth ranges (A: $h = 0.1$ to $30\,\mathrm{km}$, 553 records from 111 earthquakes; B: $h = 30$ to $60\,\mathrm{km}$, 778 records from 136 earthquakes; C: $h = 60$ to $90\,\mathrm{km}$, 526 records from 94 earthquakes; D: $h = 90$ to $120\,\mathrm{km}$, 229 records from 31 earthquakes; E: $h = 120$ to $200\,\mathrm{km}$, 112 records from 19 earthquakes) and find attenuation equations for each range. Note results from D & E may not be reliable due to small number of records. Find similar results from each group and all data together.
- Find weak correlation in station coefficients with soil categories, as defined in Iwasaki *et al.* (1980), but note large scatter.

2.118 Sarma & Free (1995)

- Ground-motion model is:

$$\begin{aligned}\log(a_h) &= C_1 + C_2 M + C_3 M^2 + C_4 \log(R) + C_5 R + C_6 S \\ \text{where } R &= \sqrt{d^2 + h_0^2}\end{aligned}$$

  where a_h is in g, $C_1 = -3.4360$, $C_2 = 0.8532$, $C_3 = -0.0192$, $C_4 = -0.9011$, $C_5 = -0.0020$, $C_6 = -0.0316$, $h_0 = 4.24$ and $\sigma = 0.424$.

- Use two site categories:

$S = 0$ Rock

$S = 1$ Soil

- Use one-stage method because of the predominance of earthquakes with single recordings in the set.
- Note that it is very important to choose a functional form based as much as possible on physical grounds because the data is sparse or non-existent for important ranges of distance and magnitude.
- Carefully verify all the distances in set.
- Use focal depths from (in order of preference): special reports (such as aftershock monitoring), local agencies and ISC and NEIS determinations. Focal depths $< 30\,\mathrm{km}$.
- Do not use M_L or m_b because of a variety of reasons. One of which is the saturation of M_L and m_b at higher magnitudes ($M_L, m_b > 6$).
- If more than one estimate of M_w made then use average of different estimates.

- Use PGAs from: a) digital or digitised analogue records which have been baseline corrected and filtered, b) data listings of various agencies and c) other literature. Difference between PGA from different sources is found to be small.

- Also derive equations assuming $C_3 = 0$ (using rock and soil records and only soil records) and $C_3 = 0$, $C_4 = -1$ and $C_6 = 0$ (using only rock records).

- Include records from Nahanni region and find similar results.

- Also derive equations for Australia (115 records from 86 earthquakes, $2.4 \leq M_w \leq 6.1$, $1 \leq d_e \leq 188\,\mathrm{km}$) and N. E. China (Tangshan) (193 records from 64 earthquakes, $3.5 \leq M_w \leq 7.5$, $2 \leq d_e \leq 199\,\mathrm{km}$) . Find considerable difference in estimated PGAs using the equations for the three different regions.

2.119 Ambraseys *et al.* (1996) & Simpson (1996)

- Ground-motion model is:

$$\begin{aligned} \log y &= C_1' + C_2 M + C_4 \log r + C_A S_A + C_S S_S \\ \text{where } r &= \sqrt{d^2 + h_0^2} \end{aligned}$$

  where y is in g, $C_1' = -1.48$, $C_2 = 0.266$, $C_4 = -0.922$, $C_A = 0.117$, $C_S = 0.124$, $h_0 = 3.5$ and $\sigma = 0.25$.

- Use four site conditions but retain three (because only three records from very soft (L) soil which combine with soft (S) soil category):

  R Rock: $V_s > 750\,\mathrm{m/s}$, $\Rightarrow S_A = 0, S_S = 0$, 106 records.

  A Stiff soil: $360 < V_s \leq 750\,\mathrm{m/s}$, $\Rightarrow S_A = 1, S_S = 0$, 226 records.

  S Soft soil: $180 < V_s \leq 360\,\mathrm{m/s}$, $\Rightarrow S_A = 0, S_S = 1$, 81 records.

  L Very soft soil: $V_s \leq 180\,\mathrm{m/s}$, $\Rightarrow S_A = 0, S_S = 1$, 3 records.

- Lower limit of $M_s = 4.0$ because smaller earthquakes are generally not of engineering significance.

- Focal depths less than $30\,\mathrm{km}$, 81% between 5 and $15\,\mathrm{km}$.

- Note for some records distances have uncertainty of about $10\,\mathrm{km}$.

- Most records from distances less than about $40\,\mathrm{km}$.

- For some small events need to estimate M_s from other magnitude scales.

- Most records from free-field stations although some from basements or ground floors of relatively small structures, and tunnel portals. Do not exclude records from instruments beyond cutoff distance because of limited knowledge about triggered level.

- All uncorrected records plotted, checked and corrected for spurious points and baseline shifts.

- Uniform correction procedure was applied for all records. For short records ($< 5\,\mathrm{s}$) a parabolic adjustment was made, for long records ($> 10\,\mathrm{s}$) filtering was performed with pass band 0.20 to $25\,\mathrm{Hz}$ and for intermediate records both parabolic and filtering performed and the most realistic record was chosen. Instrument correction not applied due to limited knowledge of instrument characteristics.

- Also analyze using one-stage method, note results comparable.

2.120 Ambraseys & Simpson (1996) & Simpson (1996)

- Based on Ambraseys *et al.* (1996), see Section 2.119.

- Coefficients are: $C_1' = -1.74$, $C_2 = 0.273$, $C_4 = -0.954$, $C_A = 0.076$, $C_S = 0.058$, $h_0 = 4.7$ and $\sigma = 0.26$.

2.121 Aydan *et al.* (1996)

- Ground-motion model is:

$$a_{\max} = a_1[\exp(a_2 M_s)\exp(a_3 R) - a_4]$$

  where $a_{\max}$ is in gal, $a_1 = 2.8$, $a_2 = 0.9$, $a_3 = -0.025$ and $a_4 = 1$ (σ is not given).

- Most records from $r_{hypo} > 20\,\mathrm{km}$.

- Note that data from Turkey is limited and hence equation may be refined as amount of data increases.

- Also give equation to estimate ratio of vertical PGA (a_v) to horizontal PGA (a_h): $a_v/a_h = 0.217 + 0.046M_s$ (σ is not given).

2.122 Bommer *et al.* (1996)

- Ground-motion model is:

$$\ln(A) = a + bM + d\ln(R) + qh$$

  where h is focal depth, A is in g, $a = -1.47$, $b = 0.608$, $d = -1.181$, $q = 0.0089$ and $\sigma = 0.54$.

- Only use subduction earthquakes.

- Do not recommend equation used for hazard analysis, since derive it only for investigating equations of Climent *et al.* (1994).

2.123 Crouse & McGuire (1996)

- Ground-motion model is:

$$\ln Y = a + bM + d\ln(R + c_1\exp\{c_2M\}) + eF$$

where Y is in g, for site category B: $a = -2.342699$, $b = 1.091713$, $c_1 = 0.413033$, $c_2 = 0.623255$, $d = -1.751631$, $e = 0.087940$ and $\sigma = 0.427787$ and for site category C: $a = -2.353903$, $b = 0.838847$, $c_1 = 0.305134$, $c_2 = 0.640249$, $d = -1.310188$, $e = -0.051707$ and $\sigma = 0.416739$.

- Use four site categories, $\bar{V}_s$ is shear-wave velocity in upper $100\,\mathrm{ft}$ ($30\,\mathrm{m}$):

  A Rock: $\bar{V}_s \geq 2500\,\mathrm{fps}$ ($\bar{V}_s \geq 750\,\mathrm{m/s}$), 33 records

  B Soft rock or stiff soil: $1200 \leq \bar{V}_s \leq 2500\,\mathrm{fps}$ ($360 \leq \bar{V}_s < 750\,\mathrm{m/s}$), 88 records

  C Medium stiff soil: $600 \leq \bar{V}_s < 1200\,\mathrm{fps}$ ($180 \leq \bar{V}_s < 360\,\mathrm{m/s}$), 101 records

  D Soft clay: $\bar{V}_s < 600\,\mathrm{fps}$ ($\bar{V}_s < 180\,\mathrm{m/s}$), 16 records

- Use two source mechanisms: reverse (R): $\Rightarrow F = 1$, 81 records and strike-slip (S) $\Rightarrow F = 0$, 157 records. Most (77) reverse records from $M_s \leq 6.7$.

- Most (231) records from small building (up to 3 storeys in height) or from instrument shelters to reduce effect of soil-structure interaction. 6 records from 6 storey buildings and 1 record from a 4 storey building, included because lack of data in site or distance range of these records. Structures thought not to appreciably affect intermediate or long period and at large distances short period ground motion more greatly diminished than long period so less effect on predictions.

- Exclude records from Eureka-Ferndale area in N. California because may be associated with subduction source, which is a different tectonic regime than rest of data. Also excluded Mammoth Lake records because active volcanic region, atypical of rest of California.

- Include one record from Tarzana Cedar Hills although exclude a different record from this station due to possible topographic effects.

- Most records between $6 \leq Ms \leq 7.25$ and $10 \leq R \leq 80\,\mathrm{km}$.

- Apply weighted regression separately for site category B and C. Data space split into 4 magnitude (6.0–6.25, 6.25–6.75, 6.75–7.25, 7.25+) and 5 distance intervals ($\leq 10\,\mathrm{km}$, 10–20 km, 20–40 km, 40–80 km, 80 km+). Each recording within bin given same total weight.

- So that Y is increasing function of M and decreasing function of R for all positive M and R apply constraints. Define $g = b/d$ and $h = -(g + c_2)$, then rewrite equation $\ln Y = a + d\{gM + \ln[R + c_1\exp(c_2M)]\} + eF$ and apply constraints $g \leq 0$, $d \leq 0$, $c \geq 0$, $c_2 \geq 0$ and $h \geq 0$.

- Check plots of residuals (not shown in paper), find uniform distribution.

- Find e not significantly different than 0 and inconsistency in results between different soil classes make it difficult to attach any significance to fault type.

- Lack of records for A and D site categories. Find scale factors $k_1 = 0.998638$ and $k_2 = 1.200678$ so that $Y_A = k_1 Y_B$ and $Y_D = k_2 Y_C$, where Y_S is predicted ground motion for site class S. Find no obvious dependence of k_1 or k_2 on acceleration from examining residuals. Find k_1 and k_2 not significantly different than 1.
- Note limited data for $R < 10\,\mathrm{km}$, advise caution for this range.
- Note equation developed to estimate site-amplification factors not for seismic hazard analysis.

2.124 Free (1996) & Free *et al.* (1998)

- Ground-motion model is:

$$\begin{aligned}\log(Y) &= C_1 + C_2\mathbf{M} + C_3\mathbf{M}^2 + C_4\log(R) + C_5(R) + C_6(S)\\ R &= \sqrt{d^2 + h_0^2}\end{aligned}$$

  where Y is in g, for $\mathbf{M} > 1.5$ using acceleration and velocity records, for horizontal PGA $C_1 = -4.2318$, $C_2 = 1.1962$, $C_3 = -0.0651$, $C_4 = -1$, $C_5 = -0.0019$, $C_6 = 0.261$, $h_0 = 2.9$ and $\sigma = 0.432$ and for vertical PGA $C_1 = -4.1800$, $C_2 = 1.0189$, $C_3 = -0.0404$, $C_4 = -1$, $C_5 = -0.0019$, $C_6 = 0.163$, $h_0 = 2.7$ and $\sigma = 0.415$.

- Use two site categories:

$S = 0$ Rock, H: 470 records, V: 395 records.

$S = 1$ Soil, H: 88 records, V: 83 records.

  Note that not most accurate approach but due to lack of site information consider this technique makes most consistent use of available information.

- Select data using these criteria:
  1. Epicentre and recording station must be within the stable continental region boundaries defined by Johnston *et al.* (1994) because a) such regions form end of spectrum of regions described by 'intraplate' and hence allows differences with interplate regions to be seen, b) they are clearly delineated regions and c) intraplate oceanic crust is excluded.
  2. Minimum magnitude level $\mathbf{M} = 1.5$.
  3. Use records from dam abutments and downstream free-field sites but excludes records from crests, slopes, toes, galleries, or basements.
  4. Use records from acceleration and velocity instruments.
  5. Specify no minimum PGA.
  6. Specify no maximum source distance. Do not exclude records from distances greater than shortest distance to a non-triggered station.
- Data from Australia, N.W. Europe, Peninsular India and E. N. America.
- Focal depths, $2 \leq h \leq 28\,\mathrm{km}$.
- Most records from $\mathbf{M} < 4.0$.

- Visually inspect all records including integrated velocities and displacements, identify and remove traces dominated by noise, identify and correct transient errors (spikes, ramps, linear sections, back time steps and clipped peaks), identify scaling errors, identify and remove multiple event records. Linear baseline correct and elliptically filter with cut-off 0.25 to $0.5\,\mathrm{Hz}$ (determine frequency by visual inspection of adjusted record) and 33 to $100\,\mathrm{Hz}$ (generally pre-determined by Nyquist frequency).
- Large proportion of records from velocity time histories which differentiate to acceleration. Test time domain method (central difference technique) and frequency domain method; find very similar results. Use time domain method.
- Distribution with respect to magnitude did not allow two-stage regression technique.
- In many analyses distribution of data with respect to distance did not allow simultaneous determination of coefficients C_4 and C_5, for these cases constrain C_4 to -1.
- Test effect of minimum magnitude cut-off for two cut-offs $\mathbf{M} = 1.5$ and $\mathbf{M} = 3.5$. Find if include data from $\mathbf{M} < 3.5$ then there is substantial over prediction of amplitudes for $d < 10\,\mathrm{km}$ for large magnitudes unless include C_3 term. C_3 effectively accounts for large number of records from small magnitudes and so predictions using the different magnitude cut-offs are very similar over broad range of $\mathbf{M}$ and d.
- Try including focal depth, h, explicitly by replacing h_0 with h because h_0 determined for whole set (which is dominated by small shocks at shallow depths) may not be appropriate for large earthquakes. Find improved fit at small distances but it does not result in overall improvement in fit (σ increases); this increase thought due to large errors in focal depth determination.
- Find larger standard deviations than those found in previous studies which note may be due to intrinsic differences between regional subsets within whole set. Repeat analysis separately for Australia (for horizontal and vertical), N. America (for horizontal and vertical) and N.W. Europe (horizontal); find reduced standard deviations (although still large), C_5 varies significantly between 3 regions.
- Repeat analysis excluding velocity records.
- Also repeat analysis using only rock records.

2.125 Inan *et al.* (1996)

- Ground-motion model is:

$$\log \mathrm{PGA} = aM + b\log R + c$$

where PGA is in an unknown unit but it is probably in gal, $a = 0.65$, $b = -0.9$ and $c = -0.44$ (σ not reported).

2.126 Ohno *et al.* (1996)

- Ground-motion model is:

$$\log S(T) = a(T)M - \log X_{eq} - b(T)X_{eq} + c(T) + q\Delta s(T)$$

where $S(0.02)$ is in gal, $a(0.02) = 0.318$, $b(0.02) = 0.00164$ and $c(0.02) = 1.597$ ($\Delta s(0.02)$ and σ only given in graphs).

- Use two site conditions:

$q = 0$ Pre-Quaternary: Rock (sandstone, siltstone, shale, granite, mudstone, etc.); thickness of surface soil overlying rock is less than $10\,\mathrm{m}$; shallow soil or thin alluvium, 160 records. S-wave velocities $> 600\,\mathrm{m/s}$.

$q = 1$ Quaternary: Soil (alluvium, clay, sand, silt, loam, gravel, etc.), 336 records. S-wave velocities $\leq 600\,\mathrm{m/s}$.

Exclude records from very soft soil such as bay mud or artificial fill because few such records and ground motions may be strongly affected by soil nonlinearity.

- Use equivalent hypocentral distance, X_{eq}, because strong motion in near-source region affected from points other than nearest point on fault plane.
- Use portion of record after initial S-wave arrival.
- Approximates PGA by spectral acceleration for period of $0.02\,\mathrm{s}$ and 5% damping.
- Plot the amplitude factors from first stage against M_w; find well represented by linear function.

2.127 Romeo *et al.* (1996)

- Ground-motion model is:

$$\log \mathrm{PHA} = a_1 + a_2 M_w - \log(d^2 + h^2)^{1/2} + a_3 S$$

where PHA is in g, $a_1 = -1.870 \pm 0.182$, $a_2 = 0.366 \pm 0.032$, $a_3 = 0.168 \pm 0.045$, $h = 6\,\mathrm{km}$ and $\sigma = 0.173$ for r_{jb} and $a_1 = -2.238 \pm 0.200$, $a_2 = 0.438 \pm 0.035$, $a_3 = 0.195 \pm 0.049$, $h = 5\,\mathrm{km}$ and $\sigma = 0.190$ for r_{epi}.

- Use two site categories:

$S = 0$ Rock or stiff soils and deep alluvium.

$S = 1$ All other sites.

- Use data and functional form of Sabetta & Pugliese (1987) but use M_w instead of magnitudes used by Sabetta & Pugliese (1987).

2.128 Sarma & Srbulov (1996)

- Ground-motion model is:

$$\begin{aligned} \log(A_p/\mathrm{g}) &= b_1 + b_2 M_s + b_3 \log r + b_4 r \\ \text{where } r &= (d^2 + h_0^2)^{0.5} \end{aligned}$$

where A_p is in g, using both horizontal components $b_1 = -1.617$, $b_2 = 0.248$, $b_3 = -0.5402$, $b_4 = -0.00392$, $h_0 = 3.2$ and $\sigma = 0.26$ and for larger horizontal component $b_1 = -1.507$, $b_2 = 0.240$, $b_3 = -0.542$, $b_4 = -0.00397$, $h_0 = 3.0$ and $\sigma = 0.26$.

- Consider two soil categories but do not model:
  1. Rock
  2. Soil

  Classify sites without regard to depth and shear-wave velocity of deposits.
- Most records from W. USA but many from Europe and Middle East.
- Focal depths between 2 and $29\,\mathrm{km}$.
- Records from instruments on ground floor or in basements of buildings and structures up to 3 storeys and at free-field sites, regardless of topography.
- Records baseline corrected and low-pass filtered using elliptic filter.

2.129 Singh *et al.* (1996)

- Ground-motion model is:

$$\log_{10} \mathrm{AGM} = b_1 + 0.31M - b_3 \log R$$

  where AGM is in $\mathrm{cm/s^2}$, $b_1 = 1.14$ and $b_3 = 0.615$ (σ is not given). Note there are typographical errors in the abstract.
- Data from three earthquakes with $m_b = 5.7$, one with $m_b = 5.8$ and one with $m_b = 7.2$.
- Adopt magnitude scaling coefficient (0.31) from Boore (1983).

2.130 Spudich *et al.* (1996) & Spudich *et al.* (1997)

- Ground-motion model is:

$$\log_{10} Y = b_1 + b_2(M-6) + b_3(M-6)^2 + b_4 R + b_5 \log_{10} R + b_6 \Gamma$$
$$\text{where } R = \sqrt{r_{jb}^2 + h^2}$$

  where Y is in g, $b_1 = 0.156$, $b_2 = 0.229$, $b_3 = 0$, $b_4 = 0$, $b_5 = -0.945$, $b_6 = 0.077$, $h = 5.57$, $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2}$ where $\sigma_1 = 0.216$, $\sigma_2 = 0$, for randomly orientated component $\sigma_3 = 0.094$ and for geometric mean $\sigma_3 = 0$.
- Use two site categories (following classification of Joyner & Boore (1981)):

$\Gamma = 0$ Rock: 35 records

$\Gamma = 1$ Soil: 93 records

- Applicable for extensional regimes, i.e. those regions where lithosphere is expanding areally.
- Reject records from structures of more than two storeys or from deeply embedded basements or those which triggered on S wave.
- Include records from those instruments beyond cutoff distance, i.e. beyond first instrument which did not trigger.

- Correction technique based on uniform correction and processing. Determine pass-band for filtering based on visual inspection of Fourier amplitude spectra and doubly-integrated displacements. Apply instrument correction.

- Not enough data to be able to find all coefficients so use b_2 and b_3 from Boore *et al.* (1994a)

- Note that should only be used in distance range 0 to $70\,\mathrm{km}$ because further away ground motions tend to be over predicted.

2.131 Stamatovska & Petrovski (1996)

- Ground-motion model is:

$$\begin{aligned}\mathrm{Acc} &= \exp(b)\exp(b_M)(R_h + C)^{b_R}\\ \text{where } R_h^2 &= (R_e/\rho)^2 + h^2\\ \text{and } \rho &= \sqrt{\frac{1 + tg^2\alpha}{a^{-2} + tg^2\alpha}}\end{aligned}$$

  where Acc is in $\mathrm{cm/s^2}$, α is the azimuth of the site with respect to energy propagation pattern, $b = 3.49556$, $b_M = 1.35431$, $C = 30$, $b_R = -1.58527$, $a = 1.2$ and $\sigma = 0.48884$ (definitions of t and g are not given).

- Correct PGAs for local site effects so that PGAs used correspond to a site with a shear-wave velocity of $700\,\mathrm{m/s}$. Do not state how this is performed.

- Most records from SMA-1s.

- Not all records from free-field.

- Records from strong intermediate depth earthquakes in Vrancea region.

- Focal depths, $89.1 \leq h \leq 131\,\mathrm{km}$.

- For each of the four earthquakes, calculate coefficents in equation $\ln \mathrm{Acc} = b_0 + b_1 \ln(R_e/\rho)$, the main direction of energy propagation and the relation between the semi-axes of the ellipse in two orthogonal directions ($a : b$).

- Also calculate coefficents in equation $\ln \mathrm{Acc} = b + b_M M + b_R \ln(R_h + C)$ for different azimuth by normalising the values of R_e/ρ by the azimuth. Give coefficients for Bucharest, Valeni and Cerna Voda.

- Note that uncertainty is high and suggest this is because of distribution of data with respect to M, R_e and h, the use of data processed in different ways, soil-structure interaction and the use of an approximate correction method for local site effects.

2.132 Campbell (1997), Campbell (2000), Campbell (2001) & Campbell & Bozorgnia (1994)

- Ground-motion model (horizontal component) is:

$$\begin{aligned}
\ln A_H &= a_1 + a_2 M + a_3 \ln \sqrt{R_{\mathrm{SEIS}}^2 + [a_4 \exp(a_5 M)]^2} \\
&\quad + [a_6 + a_7 \ln R_{\mathrm{SEIS}} + a_8 M]F + [a_9 + a_{10} \ln R_{\mathrm{SEIS}}]S_{\mathrm{SR}} \\
&\quad + [a_{11} + a_{12} \ln R_{\mathrm{SEIS}}]S_{\mathrm{HR}} + f_A(D) \\
f_A(D) &= \begin{cases} 0 & \text{for} \quad D \geq 1\,\mathrm{km} \\ \{[a_{11} + a_{12} \ln(R_{\mathrm{SEIS}})] - [a_9 + a_{10} \ln(R_{\mathrm{SEIS}})]S_{\mathrm{SR}}\}(1-D)(1-S_{\mathrm{HR}}) & \text{for} \quad D < 1\,\mathrm{km} \end{cases}
\end{aligned}$$

where A_H is in g, $a_1 = -3.512$, $a_2 = 0.904$, $a_3 = -1.328$, $a_4 = 0.149$, $a_5 = 0.647$, $a_6 = 1.125$, $a_7 = -0.112$, $a_8 = -0.0957$, $a_9 = 0.440$, $a_{10} = -0.171$, $a_{11} = 0.405$, $a_{12} = -0.222$, $\sigma = 0.55$ for $A_H < 0.068\,\mathrm{g}$, $\sigma = 0.173 - 0.140 \ln(A_H)$ for $0.068\,\mathrm{g} \leq A_H \leq 0.21\,\mathrm{g}$ and $\sigma = 0.39$ for $A_H > 0.21\,\mathrm{g}$ (when expressed in terms of acceleration) and $\sigma = 0.889 - 0.0691M$ for $M < 7.4$ and $\sigma = 0.38$ for $M \geq 7.4$ (when expressed in terms of magnitude).

Ground-motion model (vertical component) is:

$$\begin{aligned}
\ln A_V &= \ln A_H + b_1 + b_2 M + b_3 \ln[R_{\mathrm{SEIS}} + b_4 \exp(b_5 M)] \\
&\quad + b_6 \ln[R_{\mathrm{SEIS}} + b_7 \exp(b_8 M)] + b_9 F
\end{aligned}$$

where A_V is in g, $b_1 = -1.58$, $b_2 = -0.10$, $b_3 = -1.5$, $b_4 = 0.079$, $b_5 = 0.661$, $b_6 = 1.89$, $b_7 = 0.361$, $b_8 = 0.576$, $b_9 = -0.11$ and $\sigma_V = \sqrt{\sigma^2 + 0.36^2}$ (where σ is standard deviation for horizontal PGA prediction).

- Uses three site categories:

$S_{\mathrm{SR}} = 0, S_{\mathrm{HR}} = 1$ Hard rock: primarily Cretaceous and older sedimentary deposits, metamorphic rock, crystalline rock and hard volcanic deposits (e.g. basalt).

$S_{\mathrm{SR}} = 1, S_{\mathrm{HR}} = 0$ Soft rock: primarily Tertiary sedimentary deposits and soft volcanic deposits (e.g. ash deposits).

$S_{\mathrm{SR}} = 0, S_{\mathrm{HR}} = 0$ Alluvium or firm soil: firm or stiff Quaternary deposits with depths greater than $10\,\mathrm{m}$.

Also includes sediment depth (D) as a variable.

- Restricts to near-source distances to minimize influence of regional differences in crustal attenuation and to avoid complex propagation effects that have been observed at longer distances.

- Excludes recordings from basement of buildings greater than two storeys on soil and soft rock, greater than five storeys on hard rock, toe and base of dams and base of bridge columns. Excludes recordings from shallow and soft soil because previous analyses showed such sites have accelerations significantly higher than those on deep, firm alluvium. Include records from dam abutments because comprise a significant number of rock recordings and due to stiff foundations are expected to be only minimally affected by dam. Some of these could be strongly affected by local topography.

- Includes earthquakes only if they had seismogenic rupture within shallow crust (depths less than about $25\,\mathrm{km}$). Includes several large, shallow subduction interface earthquakes because previous studies found similar near-source ground motions to shallow crustal earthquakes.
- Includes only earthquakes with M about 5 or larger to emphasize those ground motions of greatest engineering interest and limit analysis to more reliable, well-studied earthquakes.
- Notes that distance to seismogenic rupture is a better measure than distance to rupture or distance to surface projection because top layer of crust is non-seismogenic and will not contribute to ground motion. Give estimates for average depth to top of seismogenic rupture for hypothetical earthquakes.
- Considers different focal mechanisms: reverse (H:6, V:5), thrust (H:9, V:6), reverse-oblique (H:4, V:2) and thrust-oblique (0), total (H:19, V:13) $\Rightarrow F = 1$ (H:278 records, V:116 records) (reverse have a dip angle greater than or equal to 45°), strike-slip (H:27, V:13) $\Rightarrow F = 0$ (H:367 records, V:109 records) (strike-slip have an absolute value of rake less than or equal to 22.5° from the horizontal as measured along fault plane). There is only one normal faulting earthquakes in set of records (contributing four horizontal records) so difference is not modelled although $F = 0.5$ given as first approximation (later revised to $F = 0$).
- Mostly W. USA with 20 records from Nicaragua(1) Mexico (5), Iran (8), Uzbekistan (1), Chile (3), Armenia (1) and Turkey (1).
- Does regression firstly with all data. Selects distance threshold for each value of magnitude, style of faulting and local site condition such that the 16th percentile estimate of A_H was equal to $0.02\,\mathrm{g}$ (which corresponds to a vertical trigger of about $0.01\,\mathrm{g}$). Repeats regression repeated only with those records within these distance thresholds. Avoids bias due to non-triggering instruments.
- Finds dispersion (uncertainty) to be dependent on magnitude and PGA, models as linear functions. Finds better fit for PGA dependency.

2.133 Munson & Thurber (1997)

- Ground-motion model is:

$$\log_{10}\mathrm{PGA} = b_0 + b_1(M-6) + b_2 r - \log_{10} r + b_4 S$$
$$\text{where } r = \sqrt{d^2 + h^2}$$

  PGA is in g, $b_0 = 0.518$, $b_1 = 0.387$, $b_2 = -0.00256$, $b_4 = 0.335$, $h = 11.29$ and $\sigma = 0.237$.

- Use two site categories:

$S = 0$ Lava: 38 records

$S = 1$ Ash: $60 \lesssim V_s \lesssim 200\,\mathrm{m/s}$, 13 records

- Depths between 4 and $14\,\mathrm{km}$ with average $9.6\,\mathrm{km}$ (standard deviation $2.3\,\mathrm{km}$). Limit of $15\,\mathrm{km}$ chosen to differentiate between large tectonic earthquakes and deeper mantle events.

- Attenuation greater than for western USA due to highly fractured volcanic pile.
- Peak acceleration measured directly from accelerograms. Check against one from corrected records, small difference.
- Excludes records triggered on S-wave and those beyond cutoff distance (the distance to first nontriggered instrument).
- Does weighted and unweighted least squares analysis; find some differences.

2.134 Pancha & Taber (1997)

- Ground-motion model is:

$$\begin{aligned}\log y &= \alpha + \beta \mathbf{M} - \log r + br \\ \text{where } r &= (d^2 + h^2)^{1/2}\end{aligned}$$

  Coefficients are unknown.

- Also develop model using functional form of Molas & Yamazaki (1995).
- All data from rock sites.
- Data from seismographs of New Zealand National Seismograph Network and temporary deployments on East Cape of the North Island, the Marlborough region of the South Island and the central volcanic zone of the North Island.
- Most data from more than $100\,\mathrm{km}$ from the source.

2.135 Rhoades (1997)

- Ground-motion model is:

$$\begin{aligned}\log_{10} a &= \alpha + \beta M - \log_{10} r + \gamma r \\ \text{where } r &= (d^2 + h^2)^{1/2}\end{aligned}$$

  where a is in g, $\alpha = -1.237 \pm 0.254$, $\beta = 0.278 \pm 0.043$, $\gamma = -0.00220 \pm 0.00042$, $h = 6.565 \pm 0.547$, $\tau^2 = 0.00645 \pm 0.00382$ and $\sigma^2 = 0.0527 \pm 0.00525$ (where τ^2 is the inter-earthquake variance and σ^2 is the intra-earthquake variance and $\pm$ signifies the standard error of the estimate.

- Notes that errors in magnitude determination are one element that contributes to the between-earthquake component of variance and could thus cause apparent differences between earthquakes, even if none existed.
- Develops a method to explicitly include consideration of magnitude uncertainties in a random earthquake effects model so that the between-earthquake component of variance can be split into the part that is due only to magnitude uncertainty (and is therefore of no physical consequence) and the part for which a physical explanation may be sought.

- Applies method to data of Joyner & Boore (1981). Assume two classes of magnitude estimates: those with estimates of M_w, which assumes to be associated with a standard error of 0.1, and those for which M_L was used as a surrogate for M_w, which assumes to be associated with a standard error of 0.3. Find that the inter-earthquake variance is much lower than that computed assuming that the magnitudes are exact but that other coefficients are similar. Believes that the high inter-earthquake variance derived using the exact magnitudes model is largely explained by the large uncertainties in the magnitude estimates using M_L.

2.136 Schmidt *et al.* (1997)

- Ground-motion model is:

$$\begin{aligned} \ln A &= c_1 + c_2 M + c_3 \ln r + c_4 r + c_5 S_1 + c_6 S_2 \\ \text{where } r &= \sqrt{R^2 + 6^2} \end{aligned}$$

  where A is in $\mathrm{m/s^2}$, $c_1 = -1.589$, $c_2 = 0.561$, $c_3 = -0.569$, $c_4 = -0.003$, $c_5 = 0.173$, $c_6 = 0.279$ and $\sigma = 0.80$ (for all earthquakes), $c_1 = -1.725$, $c_2 = 0.687$, $c_3 = -0.742$, $c_4 = -0.003$, $c_5 = 0.173$, $c_6 = 0.279$ and $\sigma = 0.83$ (for shallow crustal earthquakes) and $c_1 = -0.915$, $c_2 = 0.543$, $c_3 = -0.692$, $c_4 = -0.003$, $c_5 = 0.173$, $c_6 = 0.279$ and $\sigma = 0.74$ (for subduction zone earthquakes).

- Use three site categories:

$S_1 = 0, S_2 = 0$ Rock, 54 records.

$S_1 = 1, S_2 = 0$ Hard soil, 63 records.

$S_1 = 0, S_2 = 1$ Soft soil, 83 records.

- Most records from SMA-1s with 6 records from SSA-2.
- Use PSA at $40\,\mathrm{Hz}$ ($0.025\,\mathrm{s}$) as peak ground acceleration.
- Records instrument corrected and bandpass filtered with cut-offs of 0.2 and $20\,\mathrm{Hz}$.
- Use data from shallow crustal earthquakes (133 records) and subduction zone earthquakes (67 records).
- Perform regression on combined shallow crustal and subduction zone records, on just the shallow crustal records using r_{hypo} and using r_{epi} and on just subduction zone records.
- Note that distribution w.r.t. distance improves in the near field when epicentral distance is used but only possible to use r_{epi} for shallow crustal earthquakes because for subduction zone earthquakes hypocentral distance is much greater than epicentral distance so should use r_{hypo} instead.
- For $4 \leq M \leq 6$ distribution w.r.t. epicentral distance is quite good but for $M > 6$ no records from $d_e < 40\,\mathrm{km}$.
- Use a two step procedure. Firstly use entire set and both horizontal components and compute two soil terms (one for hard and one for soft soil). In second step use soil terms to correct motions for rock conditions and then repeat regression.

- Use Bayesian analysis (Ordaz *et al.* , 1994) so that derived coefficients comply with physics of wave propagation because include *a priori* information on the coefficients to avoid physically unrealistic values. Choose initial values of coefficients based on theory and previous results
- Cannot find coefficient in r by regression so adopt $6\,\mathrm{km}$ from previous study.
- Examine residuals w.r.t. distance and magnitude and find no trends.

2.137 Youngs *et al.* (1997)

- Ground-motion model for soil is:

$$\begin{aligned}\ln \mathrm{PGA} &= C_1^* + C_2\mathbf{M} + C_3^* \ln\left[r_{\mathrm{rup}} + \mathrm{e}^{C_4^* - \frac{C_2}{C_3^*}\mathbf{M}}\right] + C_5 Z_t + C_9 H + C_{10} Z_{ss} \\ \text{with: } C_1^* &= C_1 + C_6 Z_r \\ C_3^* &= C_3 + C_7 Z_r \\ C_4^* &= C_4 + C_8 Z_r\end{aligned}$$

where PGA is in g, $C_1 = -0.6687$, $C_2 = 1.438$, $C_3 = -2.329$, $C_4 = \ln(1.097)$, $C_5 = 0.3643$, $C_9 = 0.00648$ and $\sigma = 1.45 - 0.1\mathbf{M}$ (other coefficients in equation not needed for prediction on deep soil and are not given in paper).

Ground-motion model for rock is:

$$\begin{aligned}\ln \mathrm{PGA} &= C_1^* + C_2\mathbf{M} + C_3^* \ln\left[r_{\mathrm{rup}} + \mathrm{e}^{C_4^* - \frac{C_2}{C_3^*}\mathbf{M}}\right] + C_5 Z_{ss} + C_8 Z_t + C_9 H \\ \text{with: } C_1^* &= C_1 + C_3 C_4 - C_3^* C_4^* \\ C_3^* &= C_3 + C_6 Z_{ss} \\ C_4^* &= C_4 + C_7 Z_{ss}\end{aligned}$$

where PGA is in g, $C_1 = 0.2418$, $C_2 = 1.414$, $C_3 = -2.552$, $C_4 = \ln(1.7818)$, $C_8 = 0.3846$, $C_9 = 0.00607$ and $\sigma = 1.45 - 0.1\mathbf{M}$ (other coefficients in equation not needed for prediction on rock and are not given in paper).

Use different models to force rock and soil accelerations to same level in near field.

- Use three site categories to do regression but only report results for rock and deep soil:

$Z_r = 1, Z_{ds} = 0, Z_{ss} = 0$ Rock: Consists of at most about a metre of soil over weathered rock, 96 records.

$Z_{ds} = 1, Z_r = 0, Z_{ss} = 0$ Deep soil: Depth to bedrock is greater than $20\,\mathrm{m}$, 284 records.

$Z_{ss} = 1, Z_{ds} = 0, Z_r = 0$ Shallow soil: Depth to bedrock is less than $20\,\mathrm{m}$ and a significant velocity contrast may exist within $30\,\mathrm{m}$ of surface, 96 records.

- Use free-field recordings, i.e. instruments in basement or ground-floor of buildings less than four storeys in height. Data excluded if quality of time history poor or if portion of main shaking not recorded.
- Consider tectonic type: interface (assumed to be thrust) (98 records) $\Rightarrow Z_t = 0$, intraslab (assumed to be normal) (66 records) $\Rightarrow Z_t = 1$

- Focal depths, H, between 10 and $229\,\mathrm{km}$
- Not enough data to perform individual regression on each subset so do joint regression analysis.
- Both effect of depth and tectonic type significant.
- Large differences between rock and deep soil.
- Note differences between shallow crustal and interface earthquake primarily for very large earthquakes.
- Assume uncertainty to be linear function of magnitude.

2.138 Zhao *et al.* (1997)

- Ground-motion model (Model 1) is:

$$\log_{10}\mathrm{PGA} = A_1 M_w + A_2 \log_{10}\sqrt{r^2+d^2} + A_3 h_c + A_4 + A_5\delta_R + A_6\delta_A + A_7\delta_I$$

  where PGA is in $\mathrm{m/s^2}$, $\delta_R = 1$ for crustal reverse 0 otherwise, $\delta_A = 1$ for rock 0 otherwise, $\delta_I = 1$ for interface 0 otherwise, $A_1 = 0.298$, $A_2 = -1.56$, $A_3 = 0.00619$, $A_4 = -0.365$, $A_5 = 0.107$, $A_6 = -0.186$, $A_7 = -0.124$, $d = 19$ and $\sigma = 0.230$.

- Models also given for soil sites only (Model 2), unspecified site (Model 3), focal mechanism and tectonic type unknown (Model 4) and only magnitude, depth and distance known (Model 5)
- Records from ground or base of buildings. 33 from buildings with more than 3 storeys; find no significant differences.
- Retain two site categories:
  1. Rock: Topographic effects expected, very thin soil layer ($\leq 3\,\mathrm{m}$) overlying rock or rock outcrop.
  2. Soil: everything else
- Use depth to centroid of rupture, h_c, $4 \leq h_c \leq 149$. Only nine are deeper than $50\,\mathrm{km}$. Exclude records from deep events which travelled through mantle.
- Consider tectonic type: C=crustal (24+17 records), I=interface (7+0 records) and S=slab (20+0 records)
- Consider source mechanism: N=normal (15+1 records), R=reverse (22+5 records) and S=strike-slip (12+11 records). Classify mixed mechanisms by ratio of components ≥ 1.0.
- For only five records difference between the distance to rupture surface and the distance to centroid could be more than 10%.
- 66 foreign near-source records ($d_r \leq 10\,\mathrm{km}$) from 17 crustal earthquakes supplement NZ data. Mainly from western North America including 17 from Imperial Valley and 12 from Northridge.

- Exclude one station's records (Atene A) due to possible topographical effects.
- Exclude records which could have been affected by different attenuation properties in the volcanic region.
- Note regional difference between Fiordland and volcanic region and rest of country but do model.
- Retain coefficients if significant at $\alpha = 0.05$.
- Anelastic term not significant.

2.139 Baag *et al.* (1998)

- Ground-motion model is:

$$\begin{aligned}\ln \mathrm{PGA} &= a_1 + a_2 M + a_3 \ln R + a_4 R \\ \text{where} \quad R &= \sqrt{R_{\mathrm{epi}}^2 + a_5^2}\end{aligned}$$

  where PGA is in $\mathrm{cm/s^2}$, $a_1 = 0.4$, $a_2 = 1.2$, $a_3 = -0.76$, $a_4 = -0.0094$ and $a_5 = 10$ (σ not given).

- This article has not been seen. The model presented may not be a fully empirical model.

2.140 Bouhadad *et al.* (1998)

- Ground-motion model is:

$$A = c \exp(\alpha M)[R^k + a]^{-\beta - \gamma R}$$

- Coefficients not given, only predictions.

2.141 Costa *et al.* (1998)

- Ground-motion model is:

$$\log(A) = a + bM + c \log(r)$$

  where A is in g, $a = -1.879$, $b = 0.431$ and $c = -1.908$ (for vertical components) and $a = -2.114$, $b = 0.480$ and $c = -1.693$ (for horizontal components).

- All records from digital instruments.
- Try including a term $d \log(M)$ but tests show that d is negligible with respect to a, b and c.

2.142 Manic (1998)

- Ground-motion model is:

$$\begin{aligned} \log(A) &= c_1 + c_2 M + c_3 \log(D) + c_4 D + c_5 S \\ D &= (R^2 + d_0^2)^{1/2} \end{aligned}$$

where A is in g, $c_1 = -1.664$, $c_2 = 0.333$, $c_3 = -1.093$, $c_4 = 0$, $c_5 = 0.236$, $d_0 = 6.6$ and $\sigma = 0.254$.

- Uses four site categories (following Ambraseys *et al.* (1996)) but only two have data within them:

$S = 0$ Rock (R): $v_s > 750\,\mathrm{m/s}$, 92 records.

$S = 1$ Stiff soil (A): $360 < v_s \leq 750\,\mathrm{m/s}$, 184 records.

where v_s is average shear-wave velocity in upper $30\,\mathrm{m}$.

- Uses both horizontal components to get a more reliable set of data.
- Tries using M_L rather than M_s, epicentral distance rather than hypocentral distance and constraining anelastic decay coefficient, c_4, to zero. Chooses combination which gives minimum σ.

2.143 Reyes (1998)

- Ground-motion model is:

$$\ln \mathrm{Sa} = \alpha_1 + \alpha_2(M-6) + \alpha_3(M-6)^2 + \alpha_4 \ln R + \alpha_5 R$$

where Sa is in $\mathrm{cm/s^2}$, $\alpha_1 = 5.8929$, $\alpha_2 = 1.2457$, $\alpha_3 = -9.7565 \times 10^{-2}$, $\alpha_4 = -0.50$, $\alpha_5 = -6.3159 \times 10^{-3}$ and $\sigma = 0.420$.

- Use data from one station, University City (CU) in Mexico City, a relatively firm site.

2.144 Rinaldis *et al.* (1998)

- Ground-motion model is:

$$\ln Y = C_{14} + C_{22} M + C_{31} \ln(R + 15) + C_{43} S + C_{54} F$$

where Y is in $\mathrm{cm/s^2}$, $C_{14} = 5.57$, $C_{22} = 0.82$, $C_{31} = -1.59$, $C_{43} = -0.14$, $C_{54} = -0.18$ and $\sigma = 0.68$. Assume $15\,\mathrm{km}$ inside $\ln(R + \ldots)$ from Theodulidis & Papazachos (1992).

- Use two site categories:

$S = 0$ Rock: includes stiff sites.

$S = 1$ Alluvium: includes both shallow and deep soil sites.

- Use two source mechanism categories:

$F = 0$ Thrust and strike-slip earthquakes.

$F = 1$ Normal earthquakes.

- Use epicentral distance because in Italy and Greece the surface geology does not show any evident faulting, consequently it is impossible to use a fault distance definition.

- Good distribution and coverage of data with respect to site category and source mechanism.

- Consider six strong-motion records (three Italian and three Greek) with different associated distances, magnitudes and record length and apply the different processing techniques of ENEA-ENEL and ITSAK to check if data from two databanks can be merged. Digitise six records using same equipment. ITSAK technique: subtract the reference trace (either fixed trace or trace from clock) from uncorrected accelerogram and select band-pass filter based on either Fourier amplitude spectra of acceleration components or selected using a different technique. ENEA-ENEL technique: subtract the reference trace from uncorrected accelerogram and select band-pass filter by comparing Fourier amplitude spectra of acceleration components with that of fixed trace. Find small differences in PGA, PGV, PGD so can merge Italian and Greek data into one databank.

- Use four step regression procedure, similar to that Theodulidis & Papazachos (1992) use. First step use only data with $M \geq 6.0$ ($7 \leq R \leq 138\,\mathrm{km}$) for which distances are more accurate to find geometrical coefficient C_{31}. Next find constant (C_{12}) and magnitude (C_{22}) coefficients using all data. Next find constant (C_{13}) and soil (C_{43}) coefficients using all data. Finally find constant (C_{14}) and source mechanism (C_{54}) coefficients using data with $M \geq 6.0$ for which focal mechanism is better constrained; final coefficients are C_{14}, C_{22}, C_{31}, C_{43} and C_{54}. Investigate influence of distance on C_{54} by subdividing data in final step into three categories with respect to distance ($7 \leq R \leq 140\,\mathrm{km}$, $7 \leq R \leq 100\,\mathrm{km}$ and $7 \leq R \leq 70\,\mathrm{km}$).

- Equation intended as first attempt to obtain attenuation relations from combined databanks and site characteristics and fault rupture properties could and should be taken into account.

2.145 Sadigh & Egan (1998)

- Based on Sadigh *et al.* (1997), see Section 2.77.

- Ground-motion model is:

$$\ln \mathrm{PGA} = C_1 + C_2 M + C_3 \ln[r_{\mathrm{rup}} + \exp(C_4 + C_5 M)]$$

  where PGA is in g, for $M < 6.5$ $C_4 = 1.29649$ and $C_5 = 0.25$ and for $M \geq 6.5$ $C_4 = -0.48451$ and $C_5 = 0.524$. For rock sites: $C_3 = -2.100$, for strike-slip mechanism and $M < 6.5$ $C_1 = -0.949$ and $C_2 = 1.05$, for strike-slip mechanism and $M \geq 6.5$ $C_1 = -1.274$ and $C_2 = 1.10$, for reverse-slip and $M < 6.5$ $C_1 = 0.276$ and $C_2 = 0.90$ and for reverse-slip and $M \geq 6.5$ $C_1 = -1.024$ and $C_2 = 1.10$. For soil sites: $C_3 = -1.75$, for strike-slip mechanism and $M < 6.5$ $C_1 = -1.1100$ and $C_2 = 0.875$, for strike-slip mechanism and $M \geq 6.5$ $C_1 = -1.3830$ and $C_2 = 0.917$, for reverse-slip mechanism and $M < 6.5$ $C_1 = -0.0895$ and $C_2 = 0.750$ and for reverse-slip mechanism and $M \geq 6.5$ $C_1 = -1.175$ and $C_2 = 0.917$ (σ not given).

- Use two site categories:

1. Rock: bedrock within about a metre of surface. Note that many such sites are soft rock with $V_s \leq 750\,\mathrm{m/s}$ and a strong velocity gradient because of near-surface weathering and fracturing, 274 records.
2. Deep soil: greater than $20\,\mathrm{m}$ of soil over bedrock. Exclude data from very soft soil sites such as those from San Francisco bay mud, 690 records.

- Define crustal earthquakes as those that occur on faults within upper 20 to $25\,\mathrm{km}$ of continental crust.
- Consider source mechanism: RV=reverse (26+2) and SS=strike-slip (and some normal) (89+0). Classified as RV if rake$> 45°$ and SS if rake$< 45°$. Find peak motions from small number of normal faulting earthquakes not to be significantly different than peak motions from strike-slip events so include in SS category.
- Separate equations for $M_w < 6.5$ and $M_w \geq 6.5$ to account for near-field saturation effects, for rock and deep soil sites and reverse and strike-slip earthquakes.
- Records from instruments in instrument shelters near ground surface or in ground floor of small, light structures.
- 4 foreign records (1 from Gazli and 3 from Tabas) supplement Californian records.

2.146 Sarma & Srbulov (1998)

- Ground-motion model is:

$$\log(a_p/g) = C_1 + C_2 M_s + C_3 d + C_4 \log d$$

  where a_p is in g, for soil sites $C_1 = -1.86$, $C_2 = 0.23$, $C_3 = -0.0062$, $C_4 = -0.230$ and $\sigma = 0.28$ and for rock sites $C_1 = -1.874$, $C_2 = 0.299$, $C_3 = -0.0029$, $C_4 = -0.648$ and $\sigma = 0.33$.
- Use two site categories because of limited available information (based on nature of top layer of site regardless of thickness) for which derive separate equations:
  1. Soil
  2. Rock
- Use record from free-field or in basements of buildings ≤ 3 storeys high.
- Use M_s because better represents size of shallow earthquakes and is determined from teleseismic readings with much smaller standard errors than other magnitude scales and also saturates at higher magnitudes than all other magnitude scales except M_w which is only available for relatively small portion of earthquakes. For some small earthquakes convert to M_s from other magnitude scales.
- For very short records, $\leq 5\,\mathrm{s}$ long, correct using parabolic baseline, for records $> 10\,\mathrm{s}$ long correct using elliptical filter and for records between 5 and $10\,\mathrm{s}$ long both parabolic correction and filtering applied and select best one from appearance of adjusted time histories.
- Equations not any more precise than other attenuation relations but are simply included for completeness and for a comparison of effects of dataset used with other dataset. Data did not allow distinction between different source mechanisms.

2.147 Sharma (1998)

- Ground-motion model is:

$$\log A = c_1 + c_2 M - b \log(X + e^{c_3 M})$$

  where A is in g, $c_1 = -1.072$, $c_2 = 0.3903$, $b = 1.21$, $c_3 = 0.5873$ and $\sigma = 0.14$.

- Considers two site categories but does not model:

  R Rock: generally granite/quartzite/sandstone, 41 records.

  S Soil: exposed soil covers on basement, 25 records.

- Focal depths between 7.0 and $50.0\,\mathrm{km}$.

- Most records from distances $> 50\,\mathrm{km}$. Correlation coefficient between M and X is 0.63.

- Does not include source mechanism as parameter because not well defined and including many terms may lead to errors. Also neglects tectonic type because set is small and small differences are expected.

- Fit $\log A = -b \log X + c$ to data from each earthquake separately and find average b equal to 1.292. Then fit $\log A = aM - b \log X + c$ to data from all earthquakes and find $b = 0.6884$. Fit $\log A = -b \log X + \sum d_i l_i$ to all data, where $l_i = 1$ for ith earthquake and 0 otherwise and find $b = 1.21$, use this for rest of analysis.

- Use weighted regression, due to nonuniform sampling over all M and X. Divide data into distance bins $2.5\,\mathrm{km}$ wide up to $10\,\mathrm{km}$ and logarithmically dependent for larger distances. Within each bin each earthquake is given equal weight by assigning a relative weight of $1/n_{j,l}$, where $n_{j,l}$ is the number of recordings for jth earthquake in lth distance bin, then normalise so that sum to total number of recordings.

- Original data included two earthquakes with focal depths $91.0\,\mathrm{km}$ and $119.0\,\mathrm{km}$ and $M = 6.8$ and 6.1 which caused large errors in regression parameters due to large depths so excluded them.

- Check capability of data to compute coefficients by deleting, in turn, c_1, c_2 and c_3, find higher standard deviation.

- Makes one coefficient at a time equal to values given in Abrahamson & Litehiser (1989), finds sum of squares increases.

- Notes lack of data could make relationship unreliable.

2.148 Smit (1998)

- Ground-motion model is:

$$\log Y = a + bM - \log R + dR$$

  where Y is in $\mathrm{nm/s^2}$, $b = 0.868$, $d = -0.001059$, $\sigma = 0.35$, for horizontal PGA $a = 5.230$ and for vertical PGA $a = 5.054$.

- Most records from rock sites.

- Focal depths between 0 and about $27\,\mathrm{km}$ (most less than $10\,\mathrm{km}$).
- Most records from $M_L < 3.5$.
- Most earthquakes have strike-slip mechanism.
- Uses records from high gain short period seismographs and from strong-motion instruments.
- Records are instrument corrected.
- Eliminates some far-field data from small magnitude earthquakes using signal to noise ratio criterion.
- Records cover entire azimuthal range.
- Notes that need more data in near field.
- Notes that care must be taken when using equations for prediction of ground motion in strong earthquakes ($M \approx 6$) because of lack of data.

2.149 Cabañas *et al.* (1999), Cabañas *et al.* (2000) & Benito *et al.* (2000)

- Ground-motion model is:

$$\ln A = C_1 + C_2 M + C_3(R + R_0) + C_4 \ln(R + R_0) + C_5 S$$

  where A is in $\mathrm{cm/s^2}$, $C_1 = 0$, $C_2 = 0.664$, $C_3 = 0.009$, $C_4 = -2.206$, $R_0 = 20$, $C_5 = 8.365$ (for S1), $C_5 = 8.644$ (for S2), $C_5 = 8.470$ (for S3) and $C_5 = 8.565$ (for S4) for horizontal PGA using r_{epi} and M_s and all Mediterranean data, $C_1 = 0$, $C_2 = 0.658$, $C_3 = 0.008$, $C_4 = -2.174$, $R_0 = 20$, $C_5 = 7.693$ (for S1), $C_5 = 7.915$ (for S2) and $C_5 = 7.813$ (for S4) (C_5 not derived for S3) for vertical PGA using r_{epi} and M_s and all Mediterranean data. σ is not given (R^2 is reported).

- Use four site categories:

  S1 Hard basement rock.

  S2 Sedimentary rock and conglomerates.

  S3 Glacial deposits.

  S4 Alluvium and consolidated sediments.

- Derive separate equations using data from Mediterranean region and also just using data from Spain.
- Equations for Spain derived using m_{bLg}.
- Spanish data all from earthquakes with $2.5 \leq m_{bLg} \leq 6.0$ and $0 \leq r_{hypo} \leq 300\,\mathrm{km}$.

2.150 Chapman (1999)

- Ground-motion model is:

$$\log_{10} Y = a + b(M-6) + c(M-6)^2 + d\log(r^2+h^2)^{1/2} + eG_1 + fG_2$$

where Y is in $\mathrm{cm/s^2}$, $a = 3.098$, $b = 0.3065$, $c = -0.07570$, $d = -0.8795$, $h = 6.910$, $e = 0.1452$, $f = 0.1893$ and $\sigma = 0.2124$.

- Use three site categories:

A & B $V_{s,30} > 760\,\mathrm{m/s}$, 24 records $\Rightarrow G_1 = 0, G_2 = 0$.

C $360 < V_{s,30} \leq 760\,\mathrm{m/s}$, 116 records $\Rightarrow G_1 = 1, G_2 = 0$.

D $180 < V_{s,30} \leq 360\,\mathrm{m/s}$, 164 records $\Rightarrow G_1 = 0, G_2 = 1$.

- Uses records from ground level or in basements of structures of two stories or less, and excludes records from dam or bridge abutments.
- Selects records which include major motion portion of strong-motion episode, represented by S wavetrain. Excludes records triggered late on S wave or those of short duration terminating early in coda.
- Most records already corrected. Some records instrument corrected and 4-pole causal Butterworth filtered (corner frequencies 0.1 and $25\,\mathrm{Hz}$). Other records instrument corrected and 4-pole or 6-pole causal Butterworth bandpass filtered (corner frequencies 0.2 and $25\,\mathrm{Hz}$). All data filtered using 6-pole causal high-pass Butterworth filter with corner frequency $0.2\,\mathrm{Hz}$ and velocity and displacement curves examined.
- Uses method of Campbell (1997) to reduce bias due to non-triggered instruments, for some recent shocks. Firstly uses all data to determine minimum distances (which are functions of magnitude and site condition) at which 16th percentile values of PGA are $<$ $0.02\,\mathrm{g}[0.2\,\mathrm{m/s}]$ (corresponding to $0.01\,\mathrm{g}[0.1\,\mathrm{m/s}]$ vertical component trigger threshold). Next delete records from larger distances and repeat regression.
- Check residuals against distance and magnitude for each site class; find no obvious non-normal magnitude or distance dependent trends.

2.151 Cousins *et al.* (1999)

- Based on Zhao *et al.* (1997) see Section 2.138
- Ground-motion model is:

$$\begin{aligned}\log_{10}\mathrm{PGA} &= A_1M_w + A_2\log_{10}R + A_3h_c + A_4 + A_5 + A_6 + A_7R + A_8M_w + A_9 \\ &\quad + A_{10}R_v\end{aligned}$$

where PGA is in $\mathrm{m/s^2}$, $R = \sqrt{r^2+d^2}$ and R_v is distance travelled by direct seismic wave through volcanic region. A_5 only for crustal reverse, A_6 only for interface, A_7 only for strong and weak rock, A_8 only for strong rock, A_9 only for strong rock, $A_1 = 0.2955$, $A_2 = -1.603$, $A_3 = 0.00737$, $A_4 = -0.3004$, $A_5 = 0.1074$, $A_6 = -0.1468$, $A_7 = -0.00150$, $A_8 = 0.3815$, $A_9 = -2.660$, $A_{10} = -0.0135$, $d = 19.0$ and $\sigma = 0.24$.

- Originally considers five site categories but retain three:
  1. Strong rock: $V_s > 700\,\mathrm{m/s}$
  2. Weak rock: $375 \leq V_s \leq 700\,\mathrm{m/s}$ and category AV those sites with a very thin layer ($\leq 3\,\mathrm{m}$) overlying rock
  3. Soil: everything else
- Depth to centroid of rupture, h_c, used, $4 \leq h_c \leq 94\,\mathrm{km}$.
- 60% on soil, 40% on rock
- Consider tectonic type: C=Crustal (12+17), I=Interface (5+0) and S=Slab(8+0)
- Consider source mechanism: N=normal (6+1), R=reverse (12+5) and S=strike-slip (7+11). Mixed classified by ratio of components ≥ 1.0.
- Mixture of analogue and digital accelerograms (72%) and seismograms (28%)
- Accelerograms sampled at 100–250 samples/sec. Bandpass frequencies chosen by analysis of Fourier amplitude spectrum compared with noise spectrum. $f_{\min}$ between 0.15 and $0.5\,\mathrm{Hz}$ and $f_{\max}$ equal to $25\,\mathrm{Hz}$. Instrument correction applied to analogue records.
- Seismograms sampled at 50–100 samples/sec. Differentiated once. Instrument corrected and high pass filtered with $f_{\min} = 0.5\,\mathrm{Hz}$. No low pass filter needed.
- Clipped seismograms usually retained.
- Directional effect noticed but not modelled.
- Most records from more than $100\,\mathrm{km}$ away. Note lack of near-source data.
- Records from accelerograms further away than first operational non-triggering digital accelerograph, which had a similar triggering level, were excluded.
- Models difference between high attenuating volcanic and normal regions.

2.152 Ólafsson & Sigbjörnsson (1999)

- Ground-motion model is:

$$\log(a_{\max}) = \phi_1 + \phi_2 \log M_0 - \phi_3 \log(R)$$

  where $a_{\max}$ is in $\mathrm{cm/s^2}$, M_0 is in $\mathrm{dyn\,cm}$ and R is in cm, $\phi_1 = 0.0451$, $\phi_2 = 0.3089$, $\phi_3 = 0.9642$ and $\sigma = 0.3148$.
- Instruments in basement of buildings located on rock or very stiff ground.
- Records from 21 different stations.
- Focal depths between 1 and $11\,\mathrm{km}$.
- Most records from digital instruments with $200\,\mathrm{Hz}$ sampling frequency and high dynamic range.
- Seismic moments calculated using the strong-motion data.
- Most data from $M_0 \leq 5 \times 10^{23}\mathrm{dyn\,cm}$ and from $d_e \leq 40\,\mathrm{km}$.

2.153 Si & Midorikawa (1999, 2000)

- Ground-motion model for rupture distance is:

$$\log A = aM_w + hD + \sum d_i S_i + e - \log(X + c_1 10^{c_2 M_w}) - kX$$

where A is in $\mathrm{cm/s^2}$, $a = 0.50$, $h = 0.0036$, $d_1 = 0$, $d_2 = 0.09$, $d_3 = 0.28$, $e = 0.60$, $k = 0.003$ and $\sigma = 0.27$ (c_1 and c_2 are not given).

Ground-motion model for equivalent hypocentral distance (EHD) is:

$$\log A = aM_w + hD + \sum d_i S_i + e - \log X_{eq} - kX_{eq}$$

where A is in $\mathrm{cm/s^2}$, $a = 0.50$, $h = 0.0043$, $d_1 = 0$, $d_2 = 0.01$, $d_3 = 0.22$, $e = 0.61$, $k = 0.003$ and $\sigma = 0.28$.

- Use two site categories for most records following Joyner & Boore (1981):
    1. Rock
    2. Soil
- Records from free-field or small buildings where soil-structure interaction effects are negligible.
- Records from three different type of instrument so instrument correct. Filter with corner frequencies, chosen according to noise level, a) 0.08 & $0.15\,\mathrm{Hz}$, b) 0.10 & $0.20\,\mathrm{Hz}$ or c) 0.15 to $0.33\,\mathrm{Hz}$.
- Exclude records obviously affected by soil liquefaction.
- Focal depth (defined as average depth of fault plane), D, between 6 and $120\,\mathrm{km}$; most less than $40\,\mathrm{km}$.
- Select records satisfying: distances $< 300\,\mathrm{km}$ for $M_w > 7$, distances $< 200\,\mathrm{km}$ for $6.6 \leq M_w \leq 7$, distances $< 150\,\mathrm{km}$ for $6.3 \leq M_w \leq 6.5$ and distances $< 100\,\mathrm{km}$ for $M_w < 6.3$.
- Fix $k = 0.003$.
- Multiply rock PGAs by 1.4 to get soil PGA based on previous studies.
- Use three fault types: crustal (<719 records from 9 earthquakes) $\Rightarrow S_1 = 1, S_2 = 0, S_3 = 0$, inter-plate (<291 records from 7 earthquakes) $\Rightarrow S_2 = 1, S_1 = 0, S_3 = 0$ and intra-plate (<127 records from 5 earthquakes) $\Rightarrow S_3 = 1, S_1 = 0, S_2 = 0$.
- Use weighted regression giving more weight to near-source records (weight factor of 8 for records $< 25\,\mathrm{km}$, 4 for records between 20 and $50\,\mathrm{km}$, 2 for records between 50 and $100\,\mathrm{km}$ and 1 for records $> 100\,\mathrm{km}$). Use only three earthquakes with sufficient near-source data to find c_1 and c_2 then use all earthquakes to find a, h, d_i, e in second stage using weighted regression dependent on number of recordings for each earthquake (weight factor of 3 for $>$83 records, 2 for between 19 and 83 records, 1 for $<$19 records.
- Note that M_w and D are positively correlated so a and h may not be correctly determined when using rupture distance. Constrain a for rupture distance model to that obtained for EHD and constrain PGA to be independent of magnitude at $0\,\mathrm{km}$ and repeat regression. Coefficients given above.

2.154 Spudich *et al.* (1999) & Spudich & Boore (2005)

- Update of Spudich *et al.* (1997) see Section 2.130.
- Ground-motion model is:

$$\begin{aligned}\log_{10} Z &= b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \log_{10} D + b_6\Gamma \\ \text{with: } D &= \sqrt{r_{jb}^2 + h^2}\end{aligned}$$

  where Z is in g, $b_1 = 0.299$, $b_2 = 0.229$, $b_3 = 0$, $b_5 = -1.052$, $b_6 = 0.112$, $h = 7.27$ and $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2}$ where $\sigma_1 = 0.172$, $\sigma_2 = 0.108$ and for randomly oriented horizontal component $\sigma_3 = 0.094$ and for larger horizontal component $\sigma_3 = 0$.

- Values of σ_3 (used to compute standard deviation for a randomly orientated component) reported in Spudich *et al.* (1999) are too large by a factor of $\sqrt{2}$.
- Use two site categories (could not use more or $V_{s,30}$ because not enough data):

$\Gamma = 0$ Rock: includes hard rock (12 records) (plutonic igneous rocks, lava flows, welded tuffs and metamorphic rocks unless severely weathered when they are soft rock), soft rock (16 records) (all sedimentary rocks unless there was some special characteristic noted in description, such as crystalline limestone or massive cliff-forming sandstone when they are hard rock) and unknown rock (8 records). 36 records in total.

$\Gamma = 1$ Soil (alluvium, sand, gravel, clay, silt, mud, fill or glacial outwash of more than $5\,\mathrm{m}$ deep): included shallow soil (8 records) (5 to $20\,\mathrm{m}$ deep), deep soil (77 records) ($> 20\,\mathrm{m}$ deep) and unknown soil (21 records). 106 records in total.

- Applicable for extensional regimes, i.e. those regions where lithosphere is expanding areally. Significantly different ground motion than non-extensional areas.
- Criteria for selection of records is: $M_w \geq 5.0$, $d_f \leq 105\,\mathrm{km}$. Reject records from structures of more than two storeys or from deeply embedded basements or those which triggered on S wave. Also reject those close to dams which may be affected by dam. Also only use records already digitised.
- Include records from those instrument beyond cutoff distance, i.e. beyond first instrument which did not trigger, because of limited records and lack of data on non-triggering.
- Not enough data to be able to find all coefficients so use b_2 and b_3 from Boore *et al.* (1993) and b_6 from Boore *et al.* (1994a).
- One-stage maximum likelihood method used because many events used which only have one record associated with them and the two-stage method underestimates the earthquake-to-earthquake component of variation in that case.
- Correction technique based on uniform correction and processing using upper, f_h, and lower, f_l, frequencies for passband based on a visual inspection of Fourier amplitude spectrum and baseline fitting with a polynomial of degree 5.
- Check to see whether normal and strike-slip earthquakes give significantly different ground motions. No significant difference.

2.155 Wang *et al.* (1999)

- Ground-motion model is:

$$\log A = a + bM_s + c\log R + dR$$

where A is in $\mathrm{cm/s^2}$, using just soil records $a = 0.430$, $b = 0.428$, $c = -0.764$, $d = -0.00480$ and $\sigma = 0.271$.

- Use records from aftershocks of Tangshan earthquake.
- Focal depths between 5.7 and $12.9\,\mathrm{km}$.
- Note M_s values used may have some systematic deviation from other regions and errors, which decrease with increasing magnitude, can reach ± 0.5.
- Errors in epicentral locations not less than $2\,\mathrm{km}$. Reject 3 records because have $R < 2\,\mathrm{km}$, if include then find standard deviation increases and c obtained is unreasonable.
- Fit equation to all data (both rock and soil) but note that only for reference. Also fit equation to soil data only ($2.1 \leq R \leq 41.3\,\mathrm{km}$, $3.7 \leq M_s \leq 4.9$, 33 records from 6 earthquakes).
- Remove all four earthquakes with $M_s < 4.0$, for which error in magnitude determination is large, and fit equation to soil data only ($2.8 \leq R \leq 41.1\,\mathrm{km}$, $4.5 \leq M_s \leq 4.9$, 13 records from 2 earthquakes). Find smaller uncertainties.
- Also fit data to $\log A = a + bM_s - c\log(R + R_0)$; find similar results.
- Also use resultant of both horizontal components; find similar results to using larger component.
- Also fit eastern North America data ($3.9 \leq R \leq 61.6\,\mathrm{km}$, $2.3 \leq M_s \leq 3.8$, 7 records from 3 earthquakes); find similar attenuation characteristics.
- All equations pass F-tests.

2.156 Zaré *et al.* (1999)

- Ground-motion model is:

$$\log A = aM - bX - d\log X + c_i S_i$$

where units of A not given (but probably $\mathrm{m/s^2}$), for vertical PGA $a = 0.362$, $b = 0.0002$, $c_1 = -1.124$, $c_2 = -1.150$, $c_3 = -1.139$, $c_4 = -1.064$, $d = 1$ and $\sigma = 0.336$ and for horizontal PGA $a = 0.360$, $b = 0.0003$, $c_1 = -0.916$, $c_2 = -0.862$, $c_3 = -0.900$, $c_4 = -0.859$, $d = 1$ and $\sigma = 0.333$.

- Use four site categories, which were based on H/V receiver function (RF) measurements (use geotechnical measurements at 50 sites and strong-motion accelerograms at other sites):

Site class 1 RF does not exhibit any significant amplification below $15\,\mathrm{Hz}$. Corresponds to rock and stiff sediment sites with average S-wave velocity in top $30\,\mathrm{m}$ ($V_{s,30}$) $> 700\,\mathrm{m/s}$. Use c_1.

Site class 2 RF exhibits a fundamental peak exceeding 3 at a frequency between 5 and $15\,\mathrm{Hz}$. Corresponds to stiff sediments and/or soft rocks with $500 < V_{s,30} \leq 700\,\mathrm{m/s}$. Use c_2.

Site class 3 RF exhibits peaks between 2 and $5\,\mathrm{Hz}$. Corresponds to alluvial sites with $300 < V_{s,30} \leq 500\,\mathrm{m/s}$. Use c_3.

Site class 4 RF exhibits peaks for frequencies $< 2\,\mathrm{Hz}$. Corresponds to thick soft alluvium. Use c_4.

- Only 100 records are associated with earthquakes with known focal mechanisms, 40 correspond to strike-slip/reverse, 31 to pure strike-slip, 24 to pure reverse and 4 to a pure vertical plane. Note that use of equations should be limited to sources with such mechanisms.
- Use only records for which the signal to noise ratio was acceptable.
- Source parameters from teleseismic studies available for 279 records.
- Calculate source parameters directly from the strong-motion records for the remaining 189 digital records using a source model. Hypocentral distance from S-P time and seismic moment from level of acceleration spectra plateau and corner frequency.
- Focal depths from 9 to $133\,\mathrm{km}$ but focal depth determination is very imprecise and majority of earthquakes are shallow.
- Suggest that whenever estimation of depth of earthquake is impossible use distance to surface projection of fault rather than hypocentral distance because differences between hypocentral and epicentral distances are not significant for shallow earthquakes.
- Also derive equations based only on data from the Zagros thrust fault zone (higher seismic activity rate with many earthquakes with $4 \leq M \leq 6$) and based only on data from the Alborz-Central Iran zone (lower seismic activity rate but higher magnitude earthquakes). Find some differences between regions.
- Investigate fixing d to 1 (corresponding to body waves) and to 0.5 (corresponding to surface waves).
- Note that there are very few (only two) near-field (from less than $10\,\mathrm{km}$ from surface fault rupture) records from earthquakes with $M_w > 6.0$ and so results are less certain for such combinations of magnitude and distance.

2.157 Ambraseys & Douglas (2000), Douglas (2001b) & Ambraseys & Douglas (2003)

- Ground-motion model is:

$$\log y = b_1 + b_2 M_s + b_3 d + b_A S_A + b_S S_S$$

where y is in $\mathrm{m/s^2}$, for horizontal PGA $b_1 = -0.659$, $b_2 = 0.202$, $b_3 = -0.0238$, $b_A = 0.020$, $b_S = 0.029$ and $\sigma = 0.214$ and for vertical PGA $b_1 = -0.959$, $b_2 = 0.226$, $b_3 = -0.0312$, $b_A = 0.024$, $b_S = 0.075$ and $\sigma = 0.270$.

Assume decay associated with anelastic effects due to large strains and cannot use both $\log d$ and d because highly correlated in near field.

- Use four site categories (often use shear-wave velocity profiles):
  - L Very soft soil: approximately $V_{s,30} < 180\,\mathrm{m/s}$, (combine with category S) $\Rightarrow S_A = 0, S_S = 1$, 4 records.
  - S Soft soil: approximately $180 \leq V_{s,30} < 360\,\mathrm{m/s} \Rightarrow S_A = 0, S_S = 1$, 87 records.
  - A Stiff soil: approximately $360 \leq V_{s,30} < 750\,\mathrm{m/s} \Rightarrow S_A = 1, S_S = 0$, 68 records.
  - R Rock: approximately $V_{s,30} > 750\,\mathrm{m/s} \Rightarrow S_A = 0, S_S = 0$, 23 records.

  where $V_{s,30}$ is average shear-wave velocity to $30\,\mathrm{m}$. Know no site category for 14 records.
- Use only records from 'near field' where importance of vertical acceleration is greatest. Select records with $M_s \geq 5.8$, $d \leq 15\,\mathrm{km}$ and focal depth $h \leq 20\,\mathrm{km}$. Do not use magnitude dependent definition to avoid correlation between magnitude and distance for the records.
- Focal depths, $1 \leq h \leq 19\,\mathrm{km}$.
- Majority (133 records, 72%) of records from W. N. America, 40 records (22%) from Europe and rest from Canada, Nicaragua, Japan and Taiwan.
- Consider three source mechanisms but do not model:
  1. Normal, 8 earthquakes, 16 records.
  2. Strike-slip, 18 earthquakes, 72 records.
  3. Thrust, 16 earthquakes, 98 records.
- Use only free-field records using definition of Joyner & Boore (1981), include a few records from structures which violate this criterion but feel that structure did not affect record in period range of interest.
- Records well distributed in magnitude and distance so equations are well constrained and representative of entire dataspace. Note lack of records from normal earthquakes. Correlation coefficient between magnitude and distance is -0.10.
- Use same correction procedure (elliptical filter with pass band 0.2 to $25\,\mathrm{Hz}$, roll-off frequency $1.001\,\mathrm{Hz}$, sampling interval $0.02\,\mathrm{s}$, ripple in pass-band 0.005 and ripple in stop-band 0.015 with instrument correction) for almost all records. Use 19 records available only in corrected form as well because in large magnitude range. Think different correction procedures will not affect results.
- Try both one-stage and two-stage regression method for horizontal PGA; find large differences in b_2 but very similar b_3. Find that (by examining cumulative frequency distribution graphs for magnitude scaling of one-stage and two-stage methods) that two-stage better represents large magnitude range than one-stage method. Examine plot of amplitude factors from first stage of two-stage method against M_s; find that amplitude factor of the two Kocaeli ($M_s = 7.8$) records is far below least squares line through the amplitude factors. Remove the two Kocaeli records and repeat analysis; find b_2 from two-stage method is changed by a lot but b_2 from one-stage method is not. Conclude two-stage method is too greatly influenced by the two records from Kocaeli and hence use one-stage method.
- Find b_2 and b_3 significantly different than 0 at 5% level but b_A and b_S not significant.

2.158 Bozorgnia *et al.* (2000)

- Ground-motion model is:

$$\begin{aligned}\ln Y &= c_1 + c_2 M_w + c_3(8.5 - M_w)^2 \\ &\quad + c_4 \ln(\{R_s^2 + [(c_5 S_{HS} + c_6\{S_{PS} + S_{SR}\} + c_7 S_{HR}) \\ &\quad \exp(c_8 M_w + c_9\{8.5 - M_w\}^2)]^2\}^{1/2}) + c_{10} F_{SS} + c_{11} F_{RV} + c_{12} F_{TH} \\ &\quad + c_{13} S_{HS} + c_{14} S_{PS} + c_{15} S_{SR} + c_{16} S_{HR}\end{aligned}$$

- Use four site categories:

  HS Holocene soil: recent alluvium $\Rightarrow S_{HS} = 1, S_{PS} = 0, S_{SR} = 0, S_{HR} = 0$.

  PS Pleistocene soil: older alluvium $\Rightarrow S_{PS} = 1, S_{HS} = 0, S_{SR} = 0, S_{HR} = 0$.

  SR Soft rock $\Rightarrow S_{SR} = 1, S_{HS} = 0, S_{PS} = 0, S_{HR} = 0$.

  HR Hard rock $\Rightarrow S_{HR} = 1, S_{HS} = 0, S_{PS} = 0, S_{SR} = 0$.

- Consider all records to be free-field.
- All earthquakes occurred in shallow crustal tectonic environment.
- Consider three source mechanisms: strike-slip ($F_{SS} = 1, F_{RV} = 0, F_{TH} = 0$) 20+ earthquakes (including 1+ normal faulting shock), reverse ($F_{RV} = 1, F_{SS} = 0, F_{TH} = 0$) 7+ earthquakes and thrust ($F_{TH} = 1, F_{SS} = 0, F_{RV} = 0$) 6+ earthquakes.
- Coefficients not given, only predictions.

2.159 Campbell & Bozorgnia (2000)

- Ground-motion model is:

$$\begin{aligned}\ln Y &= c_1 + c_2 M_w + c_3(8.5 - M_w)^2 + c_4 \ln(\{R_s^2 + [(c_5 + c_6\{S_{PS} + S_{SR}\} + c_7 S_{HR}) \\ &\quad \exp(c_8 M_w + c_9\{8.5 - M_w\}^2)]^2\}^{1/2}) + c_{10} F_{SS} + c_{11} F_{RV} + c_{12} F_{TH} \\ &\quad + c_{13} S_{HS} + c_{14} S_{PS} + c_{15} S_{SR} + c_{16} S_{HR}\end{aligned}$$

  where Y is in g, for horizontal uncorrected PGA $c_1 = -2.896$, $c_2 = 0.812$, $c_3 = 0$, $c_4 = -1.318$, $c_5 = 0.187$, $c_6 = -0.029$, $c_7 = -0.064$, $c_8 = 0.616$, $c_9 = 0$, $c_{10} = 0$, $c_{11} = 0.179$, $c_{12} = 0.307$, $c_{13} = 0$, $c_{14} = -0.062$, $c_{15} = -0.195$, $c_{16} = -0.320$ and $\sigma = 0.509$, for horizontal corrected PGA $c_1 = -4.033$, $c_2 = 0.812$, $c_3 = 0.036$, $c_4 = -1.061$, $c_5 = 0.041$, $c_6 = -0.005$, $c_7 = -0.018$, $c_8 = 0.766$, $c_9 = 0.034$, $c_{10} = 0$, $c_{11} = 0.343$, $c_{12} = 0.351$, $c_{13} = 0$, $c_{14} = -0.123$, $c_{15} = -0.138$, $c_{16} = -0.289$ and $\sigma = 0.465$, for vertical uncorrected PGA $c_1 = -2.807$, $c_2 = 0.756$, $c_3 = 0$, $c_4 = -1.391$, $c_5 = 0.191$, $c_6 = 0.044$, $c_7 = -0.014$, $c_8 = 0.544$, $c_9 = 0$, $c_{10} = 0$, $c_{11} = 0.091$, $c_{12} = 0.223$, $c_{13} = 0$, $c_{14} = -0.096$, $c_{15} = -0.212$, $c_{16} = -0.199$ and $\sigma = 0.548$ and for vertical corrected PGA $c_1 = -3.108$, $c_2 = 0.756$, $c_3 = 0$, $c_4 = -1.287$, $c_5 = 0.142$, $c_6 = 0.046$, $c_7 = -0.040$, $c_8 = 0.587$, $c_9 = 0$, $c_{10} = 0$, $c_{11} = 0.253$, $c_{12} = 0.173$, $c_{13} = 0$, $c_{14} = -0.135$, $c_{15} = -0.138$, $c_{16} = -0.256$ and $\sigma = 0.520$.

- Use four site categories:

HS Holocene soil: soil deposits of Holocene age (11,000 years or less), generally described on geological maps as recent alluvium, approximate average shear-wave velocity in top $30\,\mathrm{m}$ is $290\,\mathrm{m/s} \Rightarrow S_{HS} = 1, S_{PS} = 0, S_{SR} = 0, S_{HR} = 0$.

PS Pleistocene soil: soil deposits of Pleistocene age (11,000 to 1.5 million years) , generally described on geological maps as older alluvium or terrace deposits, approximate average shear-wave velocity in top $30\,\mathrm{m}$ is $370\,\mathrm{m/s} \Rightarrow S_{PS} = 1, S_{HS} = 0, S_{SR} = 0, S_{HR} = 0$.

SR Soft rock: primarily includes sedimentary rock deposits of Tertiary age (1.5 to 100 million years), approximate average shear-wave velocity in top $30\,\mathrm{m}$ is $420\,\mathrm{m/s}$ $\Rightarrow S_{SR} = 1, S_{HS} = 0, S_{PS} = 0, S_{HR} = 0$.

HR Hard rock: primarily includes older sedimentary rock deposits, metamorphic rock and crystalline rock, approximate average shear-wave velocity in top $30\,\mathrm{m}$ is $800\,\mathrm{m/s}$ $\Rightarrow S_{HR} = 1, S_{HS} = 0, S_{PS} = 0, S_{SR} = 0$.

- Earthquakes from shallow crustal active tectonic regions.
- Most earthquakes with $6 \leq M_w \leq 7$.
- Use three source mechanism categories:

SS Strike-slip: primarily vertical or near-vertical faults with predominantly lateral slip (includes only normal faulting earthquake in set), $\Rightarrow F_{SS} = 1, F_{RV} = 0, F_{TH} = 0$.

RV Reverse: steeply dipping faults with either reverse or reverse-oblique slip, $\Rightarrow F_{RV} = 1, F_{SS} = 0, F_{TH} = 0$.

TH Thrust: shallow dipping faults with predominantly thrust slip including blind-thrust shocks, $\Rightarrow F_{TH} = 1, F_{SS} = 0, F_{RV} = 0$.

- Consider all records to be free-field. Records from ground level in instrument shelter or a building <3 storeys high (<7 if located on hard rock). Include records from dam abutments to increase number of rock records. Exclude data from basements of buildings of any size or at toe or base of dams.
- Exclude data from $R_s > 60\,\mathrm{km}$ to avoid complicating problems related to arrival of multiple reflections from lower crust. Distance range is believed to include most ground shaking amplitudes of engineering interest, except for possibly long period spectral accelerations on extremely poor soil.
- Equations for uncorrected (Phase 1 standard level of processing) and corrected (Phase 2 standard level of processing).
- Find sediment depth (depth to basement rock) has significant effect on amplitude of ground motion and should be taken into account; it will be included once its mathematical form is better understood.

2.160 Field (2000)

- Ground-motion model is:

$$\mu(M, r_{\mathrm{jb}}, V_s) = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln[(r_{\mathrm{jb}}^2 + h^2)^{0.5}] + b_v \ln(V_s/V_a)$$

$\mu(M, r_{\rm jb}, V_s)$ is natural logarithm of ground-motion parameter (e.g. $\ln(\mathrm{PGA})$ where PGA is in g), $b_{1,ss} = 0.853 \pm 0.28$, $b_{1,rv} = 0.872 \pm 0.27$, $b_2 = 0.442 \pm 0.15$, $b_3 = -0.067 \pm 0.16$, $b_5 = -0.960 \pm 0.07$, $b_v = -0.154 \pm 0.14$, $h = 8.90\,\mathrm{km}$, $V_a = 760\,\mathrm{m/s}$, $\sigma = 0.47 \pm 0.02$ (intra-event) and $\tau = 0.23$ (inter-event). Also gives overall $\sigma = (0.93 - 0.10M_w)^{0.5}$ for $M_w \leq 7.0$ and overall $\sigma = 0.48$ for $M_w > 7.0$.

- Uses six site classes (from Wills *et al.* (2000)):

  B $760 \leq V_s \leq 1500\,\mathrm{m/s}$. Uses $V_s = 1000\,\mathrm{m/s}$ in regression. 12 records.

  BC Boundary between B and C. Uses $V_s = 760\,\mathrm{m/s}$ in regression. 36 records.

  C $360 \leq V_s \leq 760\,\mathrm{m/s}$. Uses $V_s = 560\,\mathrm{m/s}$ in regression. 16 records.

  CD Boundary between C and D. Uses $V_s = 360\,\mathrm{m/s}$ in regression. 166 records.

  D $180 \leq V_s \leq 360\,\mathrm{m/s}$. Uses $V_s = 270\,\mathrm{m/s}$ in regression. 215 records.

  DE Boundary between D and E. Uses $V_s = 180\,\mathrm{m/s}$ in regression. 2 records.

- Uses data from the SCEC Phase III strong-motion database.

- Uses three faulting mechanism classes:

  Use $b_{1,ss}$ Strike-slip. 14 earthquakes, 103 records.

  Use $b_{1,rv}$ Reverse. 6 earthquakes, 300 records.

  Use $0.5(b_{1,ss} + b_{1,rv})$ Oblique. 8 earthquakes, 46 records.

- Notes that data is unbalanced in that each earthquake has a different number of records for each site type hence it is important to correct observations for the inter-event terms before examining residuals for site effects.

- Plots average site class residuals w.r.t. BC category and the residuals predicted by equation and finds good match.

- Uses 197 records with basin-depth estimates (depth defined to the $2.5\,\mathrm{km/s}$ shear-wave velocity isosurface) to examine dependence of inter-event corrected residuals w.r.t. basin depth. Plots residuals against basin depth and fits linear function. Finds that all slopes are significantly different than zero by more than two sigmas. Finds a significant trend in subset of residuals where basin-depths are known w.r.t. magnitude hence needs to test whether basin-depth effect found is an artifact of something else. Hence derives Ground-motion models (coefficients not reported) using only subset of data for which basin-depth estimates are known and examines residuals w.r.t. basin-depth for this subset. Finds similar trends as before hence concludes found basin effect is truly an effect of the basin. Notes that basin-depth coefficients should be derived simultaneously with other coefficients but because only a subset of sites have a value this could not be done.

- Tests for nonlinearity by plotting residuals for site class D w.r.t. predicted ground motion for BC boundary. Fits linear equation. Finds slope for PGA is significantly different than zero.

- Notes that due to large number of class D sites site nonlinearity could have affected other coefficients in equation leading to less of a trend in residuals. Tests for this by plotting residuals for site classes B and BC combined w.r.t. predicted ground motion for BC boundary. Fits linear equation. Finds non-significant slopes. Notes that nonlinearity may lead to rock ground motions being underestimated by model but not enough data to conclude.

- Investigates inter-event variability estimate through Monte Carlo simulations using 250 synthetic databases because uncertainty estimate of τ was considered unreliable possibly due to limited number of events. Find that there could be a problem with the regression methodology adopted w.r.t. the estimation of τ.

- Plots squared residuals w.r.t. magnitude and fits linear equations. Finds significant trends. Notes that method could be not statistically correct because squared residuals are not Gaussian distributed.

- Plots squared residuals w.r.t. V_s and does not find a significant trend.

- Provides magnitude-dependent estimates of overall σ up to $M_w 7.0$ and constant overall σ for larger magnitudes.

- Tests normality of residuals using Kolmogorov-Smirnov test and finds that the null hypothesis cannot be rejected. Also examines theoretical quantile-quantile plots and finds nothing notable.

2.161 Jain *et al.* (2000)

- Ground-motion model is:

$$\ln(\mathrm{PGA}) = b_1 + b_2 M + b_3 R + b_4 \ln(R)$$

  where PGA is in g, for central Himalayan earthquakes $b_1 = -4.135$, $b_2 = 0.647$, $b_3 = -0.00142$, $b_4 = -0.753$ and $\sigma = 0.59$ and for non-subduction earthquakes in N.E. India $b_1 = -3.443$, $b_2 = 0.706$, $b_3 = 0$, $b_4 = -0.828$ and $\sigma = 0.44$ (coefficients of other equations not given here because they are for a particular earthquake).

- Data from strong-motion accelerographs (SMA) and converted from structural response recorders (SRR), which consist of six seismoscopes with natural periods 0.40, 0.75 and $1.25\,\mathrm{s}$ and damping levels 5 and 10%. Conversion achieved by deriving spectral amplification factors (ratio of response ordinate and PGA) using SMA recordings close to SRR, checking that these factors were independent of distance. The mean of the six estimates of PGA (from the six spectral ordinates) from each SRR are then used as PGA values. Check quality of such PGA values through statistical comparisons and discard those few which appear inconsistent.

- Data split into four categories for which derive separate equations:

  a Central Himalayan earthquakes (thrust): (32 SMA records, 117 SRR records), 3 earthquakes with $5.5 \leq M \leq 7.0$, focal depths $10 \leq h \leq 33\,\mathrm{km}$ and $2 \leq R \leq 322\,\mathrm{km}$.

  b Non-subduction earthquakes in NE India (thrust): (43 SMA records, 0 SRR records), 3 earthquakes with $5.2 \leq M \leq 5.9$, focal depths $33 \leq h \leq 49\,\mathrm{km}$ and $6 \leq R \leq 243\,\mathrm{km}$.

  c Subduction earthquakes in NE India: (33 SMA records, 104 SRR records), 1 earthquake with $M = 7.3$, focal depth $h = 90\,\mathrm{km}$ and $39 \leq R \leq 772\,\mathrm{km}$.

d Bihar-Nepal earthquake in Indo-Gangetic plains (strike-slip): (0 SMA records, 38 SRR records), 1 earthquake with $M = 6.8$, focal depth $h = 57\,\mathrm{km}$ and $42 \leq R \leq 337\,\mathrm{km}$.

- Limited details of fault ruptures so use epicentral distance.
- Use epicentral locations which give best correlation between distance and PGA.
- Find PGA not well predicted by earlier equations.
- Simple model and regression method because of limited data.
- Remove one PGA value from category b equation because significantly affecting equation and because epicentral location only approximate.
- Constrain b_3 for category b equation to zero because otherwise positive.
- Category c originally contained another earthquake (14 SMA records, $M = 6.1$, $200 \leq d \leq 320\,\mathrm{km}$) but gave very small b_2 so exclude it.
- Equations for category c and category d have b_2 equal to zero because only one earthquake.
- Find considerable differences between predicted PGA in different regions.
- Note lack of data hence use equations only as first approximation.

2.162 Kobayashi *et al.* (2000)

- Ground-motion model is:

$$\log_{10} y = aM - bx - \log(x + c10^{dM}) + eh + S_k$$

where h is focal depth, y is in $\mathrm{cm/s^2}$, $a = 0.578$, $b = 0.00355$, $e = 0.00661$, $S = -0.069$, $S_R = -0.210$, $S_H = -0.114$, $S_M = 0.023$, $S_S = 0.237$ and $\sigma_T = \sqrt{\sigma^2 + \tau^2}$ where $\sigma = 0.213$ and $\tau = 0.162$.

- Use four site categories (most data from medium and hard soils):

$S_k = S_R$ Rock

$S_k = S_H$ Hard soil

$S_k = S_M$ Medium soil

$S_k = S_S$ Soft soil

S is the mean site coefficient, i.e. when do not consider site category.

- Records interpolated in frequency domain from 0.02 to $0.005\,\mathrm{s}$ interval and displacement time history calculated using a fast Fourier transform (FFT) method having perpended to beginning and appended to end at least $5\,\mathrm{s}$ of zeros to record. Number of samples in FFT is large enough that duration used in FFT is at least twice that of selected duration for processing window so that numerical errors are small. Bandpass Ormsby filter used, with limits 0.2 and $24.5\,\mathrm{Hz}$, and displacement time history plotted. If displacement in pre- and appended portions is large then increase lower frequency limit in filter until displacements are small, using smoothed Fourier spectral amplitudes from 0.05 to $25\,\mathrm{Hz}$ to make choice.

- Most earthquakes are intra-slab.
- Note lack of near-field data for all magnitudes, most data from $> 100\,\text{km}$, therefore use coefficients, c and d, from an early study.
- Excludes data from distances greater than the distance at which an earlier study predicts $\text{PGA} < 0.02\,\text{m/s}^2$.
- Consider residuals of earthquakes in western Japan (a small subset of data) and find small difference in anelastic coefficient and focal depth coefficient but note may be due to small number of records or because type of source not modelled.
- Note model predicts intraslab motions well but significantly over predicts interface motions.
- Plots site correction factors (difference between individual site factor and mean factor for that category) and find rock sites have largest variation, which suggest due to hard and soft rock included.
- Examine residual plots. Find no significant bias.

2.163 Monguilner *et al.* (2000a)

- Ground-motion model is:

$$\log a_m = C'_0 + C_1 M + C_2 \Delta + C_3 \log \Delta + C'_4 S_r$$

where a_m is in unknown unit, $\Delta = \sqrt{\text{DE}^2 + H^2 + S^2}$, DE is epicentral distance, H is focal depth, S is fault area and $C'_0 = -1.23$, $C_1 = 0.068$, $C_2 = -0.001$ and $C_3 = -0.043$ (σ is not given). Note that there are typographical inconsistencies in the text, namely S_r maybe should be replaced by S_{al}.

- Use two site categories (based on Argentinean seismic code):

$S_r = 1$ Stiff soil (II_A).

$S_r = 0$ Intermediate stiff soil (II_B).

Since there is no geotechnical data available, classify sites, assuming a uniform surface layer, using the predominant period of ground motions estimated using Fourier spectra to get an equivalent shear-wave velocity (mainly these are between 100 and $400\,\text{m/s}$).

- Records from instruments located in basements or ground floors of relatively small buildings.
- Records from SMAC and SMA-1 instruments.
- Uniform digitisation and correction procedure applied to all records to reduce noise in high and low frequency range.
- Calculate fault area using $\log S = M_s + 8.13 - 0.6667 \log(\sigma \Delta\sigma/\mu)$ where $\Delta\sigma$ is stress drop, σ is average stress and μ is rigidity.
- Most magnitudes between 5.5 and 6.0.

- Most records from $\mathrm{DE} < 100\,\mathrm{km}$.
- Most focal depths, $H \leq 40\,\mathrm{km}$. One earthquake with $H = 120\,\mathrm{km}$.
- Use weighted regression because of a correlation between magnitude and distance of 0.35. Weight each record by $\omega_i = (\omega_M + \omega_{\mathrm{DH}})/2$ where (note there are typographical errors in formulae in paper):

$$\begin{aligned}\omega_M &= \frac{n_s(i_s)\Delta M(n_i) n_e(n_i, i_s)\Delta M_T}{n_{\mathrm{cat}}}\\ \omega_{\mathrm{DH}} &= \frac{n_s(i_s)\Delta \log \mathrm{DH}(n_i) n_e(n_i, i_s)\Delta \log \mathrm{DH}_T}{n_{\mathrm{cat}}}\\ \Delta M_T &= \frac{\sum \Delta M(n_i)}{n_{\mathrm{cat}}}\\ \Delta \log \mathrm{DH}_T &= \frac{\sum \Delta \log \mathrm{DH}(n_i)}{n_{\mathrm{cat}}}\end{aligned}$$

  where $\Delta M(n_i)$ is the width of the n_ith magnitude interval and $\Delta \log \mathrm{DH}(n_i)$ is the width of the n_ith distance interval, n_{cat} is total number of intervals, n_i the index of the interval, $n_e(n_i, i_s)$ is the number of records in interval n_i from site classification i_s and n_s is the number of records from site classification i_s. Use two site classifications, three magnitude intervals and four epicentral distance intervals so $n_{\mathrm{cat}} = 2 \times 3 \times 4 = 24$.
- First do regression on $\log a_i = C_0 + C_1 M + C_2 \Delta + C_3 \log \Delta$ and then regress residuals, ϵ_i, against $C_4 S_r + C_5 S_{al}$ where $S_{al} = 1$ if site is intermediate stiff soil and $S_{al} = 0$ otherwise. Then $C_0' = C_0 + C_5$ and $C_4' = C_4 + C_5$. Similar method to that used by Ambraseys *et al.* (1996).

2.164 Sharma (2000)

- Based on Sharma (1998), see 2.147.
- A is in g and coefficients are: $c_1 = -2.87$, $c_2 = 0.634$, $c_3 = 0.62$, $b = 1.16$ and $\sigma = 0.142$.
- Fit $\log A = -b \log X + c$ to data from each earthquake separately and find average b equal to 1.18. Then fit $\log A = aM - b \log X + c$ to data from all earthquakes and find $b = 0.405$. Fit $\log A = -b \log X + \sum d_i l_i$ to all data, where $l_i = 1$ for ith earthquake and 0 otherwise and find $b = 1.16$, use this for rest of analysis.

2.165 Smit *et al.* (2000)

- Ground-motion model is:

$$\begin{aligned}\log Y &= a + bM - \log R + dR\\ \text{where } R &= \sqrt{D^2 + h^2}\end{aligned}$$

  where Y is in $\mathrm{cm/s^2}$, $a = 0.72$, $b = 0.44$, $d = -0.00231$, $h = 4.5$ and $\sigma = 0.28$.
- Records from soil or alluvium sites.

- All records corrected.
- Note that scatter can be reduced by increasing number of records used (especially in near field), improving all seismological and local site parameters and increasing number of variables (especially in near field and those modelling local site behaviour) but that this requires much more information than is available.

2.166 Takahashi *et al.* (2000)

- Ground-motion model is:

$$\log_{10}[y] = aM - bx - \log_{10}(x + c10^{dM}) + e(h - h_c)\delta_h + S_k$$

  where y is in $\mathrm{cm/s^2}$, $a = 0.446$, $b = 0.00350$, $c = 0.012$, $d = 0.446$, $e = 0.00665$, $S = 0.941$, $S_R = 0.751$, $S_H = 0.901$, $S_M = 1.003$, $S_S = 0.995$, $\sigma_T = \sqrt{\sigma^2 + \tau^2}$ where $\sigma = 0.135$ (intra-event) and $\tau = 0.203$ (inter-event), h_c is chosen as $20\,\mathrm{km}$ because gave positive depth term.

- Use four site categories:

$S_k = S_R$ Rock

$S_k = S_H$ Hard soil

$S_k = S_M$ Medium soil

$S_k = S_S$ Soft soil

  Note site conditions for many stations are uncertain. S is the mean site term for all data.

- Note ISC focal depths, h, significant reduce prediction errors compared with JMA depths. $\delta_h = 1$ for $h \geq h_c$ and $\delta_h = 0$ otherwise.
- Most Japanese data from $x > 50\,\mathrm{km}$.
- Use 166 Californian and Chilean (from 2 earthquakes) records to control model in near source.
- Due to lack of multiple records from many sites and because c and d require near-source records use a maximum likelihood regression method of two steps. Firstly, find all coefficients using all data except those from sites with only one record associated with them and unknown site class. Next, use individual site terms for all sites so as to reduce influence of uncertainty because of approximate site classifications and find a, b, e and site terms using c and d from first step.
- Intra-event and inter-event residuals decrease with increasing magnitude.
- Conclude variation in residuals against distance is due to small number of records at short and large distances.
- Individual site factors means prediction error propagates into site terms when number of records per station is very small.
- Note model may not be suitable for seismic hazard studies because model prediction errors are partitioned into σ_T and mean site terms for a given site class. Suitable model can be derived when accurate site classifications are available.

2.167 Wang & Tao (2000)

- Ground-motion model is:

$$\log Y = C + (\alpha + \beta M)\log(R + R_0)$$

  where Y is in $\mathrm{cm/s^2}$, $C = 4.053$, $\alpha = -2.797$, $\beta = 0.251$, $R_0 = 8.84$ and $\sigma = 0.257$.

- Use same data as Joyner & Boore (1981), see Section 2.31.

- Use a two-stage method based on Joyner & Boore (1981). Firstly fit data to $\log Y = C + \sum_{i=1}^{n}(a_i E_i)\log(R_i + R_0)$, where $E_i = 1$ for records from ith earthquake and $E_i = 0$ otherwise, to find C and a_i for each earthquake. Next fit $a = \alpha + \beta M$ to find α and β using a_i from first stage.

2.168 Chang *et al.* (2001)

- Ground-motion model for shallow crustal earthquakes is:

$$\ln A = c_1 + c_2 M - c_3 \ln D_p - (c_4 - c_5 D_p)\ln D_e$$

  where A is in $\mathrm{cm/s^2}$, $c_1 = 2.8096$, $c_2 = 0.8993$, $c_3 = 0.4381$, $c_4 = 1.0954$, $c_5 = 0.0079$ and $\sigma = 0.60$.

  Ground-motion model for subduction earthquakes is:

$$\ln A = c_1' + c_2' M - c_3' \ln D_p - c_4' \ln D_h$$

  where A is in $\mathrm{cm/s^2}$, $c_1' = 4.7141$, $c_2' = 0.8468$, $c_3' = 0.17451$, $c_4' = 1.2972$ and $\sigma = 0.56$.

- Note that there is limited site information available for strong-motion stations in Taiwan so do not consider local site effects.

- Use strong-motion data from Central Weather Bureau from 1994 to 1998 because it is more numerous and of better quality than older data.

- Separate earthquakes into shallow crustal and subduction earthquakes because of different seismic attenuation and seismogenic situation for the two types of earthquake.

- Shallow crustal earthquakes are mostly due to continental deformation, shallow collision or back-arc opening or are the uppermost interface earthquakes. Focal depths depth between 1.1 and $43.7\,\mathrm{km}$ with most shallower than $20\,\mathrm{km}$. Most records from earthquakes with $4.5 \leq M_w \leq 6.0$.

- Subduction earthquakes are located in the Wadati-Benioff zone or the deep lateral collision zone and are principally intraslab. Focal depth between 39.9 and $146.4\,\mathrm{km}$.

- Do not use records from earthquakes associated with coseismic rupture because they have complex near-field source effects.

- To avoid irregularly large amplitudes at great distances reject distant data predicted to be less than trigger level plus 1 standard deviation using this threshold formula: $aM_w - b\ln D + c \geq \ln V$, where V is geometric mean of PGA equal to threshold plus 1 standard deviation. For shallow crustal earthquakes: $a = 0.64$, $b = 0.83$, $c = 2.56$ and $V = 6.93$ and for subduction earthquakes: $a = 0.76$, $b = 1.07$, $c = 3.13$ and $V = 6.79$.

- For shallow crustal earthquakes examine effect of focal depth on seismic attenuation by finding geometric attenuation rate using epicentral distance, D_e, for earthquakes with $5\,\mathrm{km}$ depth intervals. Find that deeper earthquakes have slower attenuation than shallow earthquakes. Therefore assume ground motion, A, is product of f_{source} (source effects) and $f_{\mathrm{geometrical-spreading}}$ (geometrical spreading effects) where $f_{\mathrm{source}} = C_1 \exp(c_2 M)/D_p^{-c_3}$ and $f_{\mathrm{geometrical-spreading}} = D_e^{-(c_4 - c_5 D_p)}$ where D_p is focal depth.

- For subduction earthquakes examine effect of focal depth in the same way as done for shallow crustal earthquakes but find no effect of focal depth on attenuation rate. Therefore use $f_{\mathrm{geometrical-spreading}} = D_h^{-c_4}$.

- Plot residuals of both equations against distance and find no trend.

- Note that it is important to separate subduction and shallow crustal earthquakes because of the different role of focal depth and attenuation characteristics.

- Plot residual maps of ground motion for Taiwan and find significant features showing the important effect of local structures on ground motion.

2.169 Herak *et al.* (2001)

- Ground-motion model is:

$$\log a_{\max} = c_1 + c_2 M_L + c_3 \log \sqrt{c_4^2 + D^2}$$

  where $a_{\max}$ is in g, for horizontal PGA $c_1 = -1.300 \pm 0.192$, $c_2 = 0.331 \pm 0.040$, $c_3 = -1.152 \pm 0.099$, $c_4 = 11.8 \pm 4.8\,\mathrm{km}$ and $\sigma = 0.311$ and for vertical PGA $c_1 = -1.518 \pm 0.293$, $c_2 = 0.302 \pm 0.035$, $c_3 = -1.061 \pm 0.096$, $c_4 = 11.0 \pm 5.5$ and $\sigma = 0.313$.

- Records from 39 sites. Records from instruments on ground floor or in basements of relatively small structures.

- Site information only available for a small portion of the recording sites and therefore is not considered. Believe that most sites are ‘rock’ or ‘stiff soil’.

- All records from Kinemetrics SMA-1s.

- Select records with $M_L \geq 4.5$ and $D \leq 200\,\mathrm{km}$ because of poor reliability of SMA-1 records for small earthquakes and to avoid problems related to a possible change of geometrical spreading when surface waves start to dominate over body waves at large distances.

- Bandpass filter with passbands selected for which signal-to-noise ratio is > 1. Widest passband is 0.07–$25\,\mathrm{Hz}$.

- Do not use r_{jb} because do not accurately know causative fault geometry for majority of events.

- Do not include an anelastic decay term because data is inadequate to independently determine geometric and anelastic coefficients.

- Note correlation between magnitude and distance in data distribution therefore use two-stage regression. Because many earthquakes have only a few records data is divided into classes based on magnitude (details not given).
- Most data from $M_L < 5.5$, particularly data from $D < 20\,\mathrm{km}$.
- Find all coefficients significantly different than 0 at levels exceeding 0.999.
- Also regress using one-stage method and find practically equal coefficients and larger standard errors.
- Find residuals are approximately lognormally distributed with slight asymmetry showing longer tail on positive side. Relate this to site amplification at some stations balanced by larger than expected number of slightly negative residuals.
- Find no distance or magnitude dependence of residuals.
- Compute ratio between larger and average horizontal component as 1.15.
- Believe that higher than normal σ is due to lack of consideration of site effects and due to the use of r_{epi} rather than r_{jb}.

2.170 Lussou *et al.* (2001)

- Ground-motion model is:

$$\log \mathrm{PSA}(f) = a(f)M + b(f)R - \log R + c(i,f)$$

  where $\mathrm{PSA}(f)$ is in $\mathrm{cm/s^2}$, $a(f) = 3.71 \times 10^{-1}$, $b(f) = -2.54 \times 10^{-3}$, $c(A,f) = 0.617$, $c(B,f) = 0.721$, $c(C,f) = 0.845$, $c(D,f) = 0.891$ and $\sigma = 3.13 \times 10^{-1}$.
- Use four site categories, based on $V_{s,30}$ (average shear-wave velocity in top $30\,\mathrm{m}$) as proposed in Eurocode 8:

  A $V_{s,30} > 800\,\mathrm{m/s}$. Use $c(A,f)$. 14 records.

  B $400 < V_{s,30} \leq 800\,\mathrm{m/s}$. Use $c(B,f)$. 856 records.

  C $200 < V_{s,30} \leq 400\,\mathrm{m/s}$. Use $c(C,f)$. 1720 records.

  D $100 < V_{s,30} \leq 200\,\mathrm{m/s}$. Use $c(D,f)$. 421 records.
- Good determination of site conditions between shear-wave velocities have been measured down to 10 to $20\,\mathrm{m}$ at every site. Extrapolate shear-wave velocity data to $30\,\mathrm{m}$ to find $V_{s,30}$. $V_{s,30}$ at stations is between about $50\,\mathrm{m/s}$ and about $1150\,\mathrm{m/s}$.
- Use data from Kyoshin network from 1996, 1997 and 1998.
- All data from free-field sites.
- No instrument correction needed or applied.
- Use data from earthquakes with $M_{\mathrm{JMA}} > 3.5$ and focal depth $< 20\,\mathrm{km}$ because want to compare results with Ambraseys *et al.* (1996) and Boore *et al.* (1997). Also this criteria excludes data from deep subduction earthquakes and data that is not significant for seismic hazard studies.

- Homogeneous determination of JMA magnitude and hypocentral distance.
- Roughly uniform distribution of records with magnitude and distance.
- Assume pseudo-spectral acceleration for 5% damping at $0.02\,\mathrm{s}$ equals PGA.
- Note equation valid for $3.5 \leq M_{\mathrm{JMA}} \leq 6.3$ and $10 \leq r_{hypo} \leq 200\,\mathrm{km}$.
- Find inclusion of site classification has reduced standard deviation.

2.171 Sanchez & Jara (2001)

- Ground-motion model is:

$$\log(A_{\max}) = aM_s + b\log R + c$$

where the units of $A_{\max}$ are not given[7], $a = 0.444$, $b = -2.254$ and $c = 4.059$ (σ is not given).

- Use one site category: firm ground.

2.172 Wu *et al.* (2001)

- Ground-motion model is:

$$\log_{10}(Y) = C_1 + C_2M_w - \log_{10}(r_{\mathrm{rup}} + h) + C_3r_{\mathrm{rup}}$$

where Y is in $\mathrm{cm/s^2}$, $C_1 = 0.00215$, $C_2 = 0.581$, $C_3 = -0.00414$, $h = 0.00871 \times 10^{0.5M_w}$ from the square root of the expected rupture area and $\sigma = 0.79$ (in terms of natural logarithms not common logarithms).

- Select data from events with $M_L > 5$ and focal depths $< 35\,\mathrm{km}$ to restrict interest to large shallow earthquakes, which cause most damage.
- Focal depths between 1.40 and $34.22\,\mathrm{km}$.
- Relocate events using available data.
- Develop empirical relationship to convert M_L to M_w.
- Develop relation for use in near real-time (within $2\,\mathrm{min}$) mapping of PGA following an earthquake.
- Select records from the Taiwan Rapid Earthquake Information Release System (TREIRS) and records from the TSMIP if $r_{\mathrm{rup}} < 30\,\mathrm{km}$ so as not to bias the results at larger distances by untriggered instruments.
- Most data from $50 \leq d_r \leq 200\,\mathrm{km}$ and $5 \leq M_w \leq 6$.
- Compute site correction factors for TSMIP stations (since these sites have not been well classified), S, by averaging residuals between observed and predicted values. After applying these site amplifications in regression analysis obtain reduced σ of 0.66.
- Display inter-event residuals w.r.t. M_w before and after site correction.

[7] There could be a typographical error in the article since the use of common (base ten) logarithms leads to very large ground motions — the authors may mean natural logarithms.

2.173 Chen & Tsai (2002)

- Ground-motion model is:

$$\log_{10} \mathrm{PGA} = \theta_0 + \theta_1 M + \theta_2 M^2 + \theta_3 R + \theta_4 \log_{10}(R + \theta_5 10^{\theta_6 M})$$

  where PGA is in $\mathrm{cm/s^2}$, $\theta_0 = -4.366 \pm 2.020$, $\theta_1 = 2.540 \pm 0.714$, $\theta_2 = -0.172 \pm 0.0611$, $\theta_3 = 0.00173 \pm 0.000822$, $\theta_4 = -1.845 \pm 0.224$, $\theta_5 = 0.0746 \pm 0.411$, $\theta_6 = 0.221 \pm 0.405$, $\sigma_e^2 = 0.0453 \pm 0.0113$ (earthquake-specific variance), $\sigma_s^2 = 0.0259 \pm 0.00699$ (site-specific variance) and $\sigma_r^2 = 0.0297 \pm 0.00235$ (record-specific variance). $\pm$ signifies the estimated standard errors.

- Records from 45 stations on rock and firm soil. All sites have more than two records.
- Use a new estimation procedure where the residual variance is decomposed into components due to various source of deviations. Separate variance into earthquake-to-earthquake variance, site-to-site variance and the remainder.
- Proposed method does not require additional regression or searching procedures.
- Perform a simulation study and find proposed procedure yields estimates with smaller biases and take less computation time than do other similar regression techniques.
- Visually examine the equation for various magnitude values before regressing.

2.174 Gregor *et al.* (2002a)

- Ground-motion model is (their model D):

$$\begin{aligned}\ln \mathrm{GM} &= \theta_1 + \theta_2 M + (\theta_3 + \theta_4 M) \ln[D + \exp(\theta_5)] + \theta_6(1 - S) + \theta_7(M-6)^2 + \theta_8 F \\ &\quad + \theta_9 / \tanh(D + \theta_{10})\end{aligned}$$

  where GM is in g, $\theta_1 = 4.31964$, $\theta_2 = -0.00175$, $\theta_3 = -2.40199$, $\theta_4 = 0.19029$, $\theta_5 = 2.14088$, $\theta_6 = 0.09754$, $\theta_7 = -0.21015$, $\theta_8 = 0.38884$, $\theta_9 = -2.29732$, $\theta_{10} = 448.88360$, $\sigma = 0.5099$ (intra-event) and $\tau = 0.4083$ (inter-event) for horizontal PGA using the static dataset without the Chi-Chi data and $\theta_1 = 1.50813$, $\theta_2 = 0.15024$, $\theta_3 = -2.52562$, $\theta_4 = 0.17143$, $\theta_5 = 2.12429$, $\theta_6 = 0.10517$, $\theta_7 = -0.16655$, $\theta_8 = 0.22243$, $\theta_9 = -0.11214$, $\theta_{10} = 19.85830$, $\sigma = 0.5141$ (intra-event) and $\tau = 0.4546$ (inter-event) for vertical PGA using the static dataset without the Chi-Chi data. Coefficients are also given for the three other models and for both the dynamic and the static datasets but are not reported here due to lack of space.

- Use two site categories:

$S = 0$ Soil: includes sites located on deep broad and deep narrow soil deposits.

$S = 1$ Rock: includes sites that are located on shallow stiff soil deposits;

- Use three rupture mechanism categories:

$F = 0$ Strike-slip, 39 earthquakes, 387 records;

$F = 0.5$ Reverse/oblique, 13 earthquakes, 194 records;

$F = 1$ Thrust, 16 earthquakes, 412 records.

- Process records using two procedures as described below.
  1. Use the standard PEER procedure with individually chosen filter cut-offs.
  2. Fit the original integrated velocity time-history with three different functional forms (linear in velocity; bilinear, piecewise continuous function; and quadratic in velocity). Choose the 'best-fit' result and view it for reasonableness. Differentiate the velocity time-history and then low-pass filter with a causal Butterworth filter with cut-offs about $50\,\mathrm{Hz}$.
- PGA values from the two processing techniques are very similar.
- Investigate using a nonlinear model for site response term but the resulting models did not improve the fit.
- Also try three other functional forms:

$$\begin{aligned}\ln(\mathrm{GM}) &= \theta_1+\theta_2M+\theta_3\ln[D+\theta_4\exp(\theta_5M)]+\theta_6(1-S)+\theta_7F\\ \ln(\mathrm{GM}) &= \theta_1+\theta_2M+(\theta_3+\theta_4M)\ln[D+\exp(\theta_5)]+\theta_6(1-S)+\theta_7(M-6)^2+\theta_8F\\ \ln(\mathrm{GM}) &= \theta_1+\theta_2M+\theta_3\ln[D+\exp(\theta_5M)]+\theta_6(1-S)+\theta_7F+\theta_8/\tanh(D+\theta_9)\end{aligned}$$

  which all give similar standard deviations and predictions but prefer model D.
- Models oversaturate slightly for large magnitudes at close distances. Therefore recommend that the PGA equations are not used because this oversaturation is based on very little data.
- Because the Chi-Chi short period ground motions may be anomalous relative to California they develop equations including and excluding the Chi-Chi data, which only affects predictions for large magnitudes ($M > 7.5$).

2.175 Gülkan & Kalkan (2002)

- Ground-motion model is:

$$\begin{aligned}\ln Y &= b_1+b_2(M-6)+b_3(M-6)^2+b_5\ln r+b_V\ln(V_S/V_A)\\ \text{where } r &= (r_{\mathrm{cl}}^2+h^2)^{1/2}\end{aligned}$$

  where Y is in g, $b_1=-0.682$, $b_2=0.253$, $b_3=0.036$, $b_5=-0.562$, $b_V=-0.297$, $V_A=1381$, $h=4.48$ and $\sigma=0.562$.
- Use three site categories:

  Soft soil Average shear-wave velocity, V_S, is $200\,\mathrm{m/s}$. 40 records.

  Soil Average shear-wave velocity, V_S, is $400\,\mathrm{m/s}$. 24 records.

  Rock Average shear-wave velocity, V_S, is $700\,\mathrm{m/s}$. 29 records.

  Actual shear-wave velocities and detailed site descriptions are not available for most stations in Turkey. Therefore estimate site classification by analogy with information in similar geologic materials. Obtain type of geologic material in number of ways: consultation with geologists at Earthquake Research Division of Ministry of Public Works and Settlement, various geological maps, past earthquake reports and geological references prepared for Turkey.

- Only used records from small earthquakes recorded at closer distances than large earthquakes to minimize the influence of regional differences in attenuation and to avoid the complex propagation effects coming from longer distances.
- Only use records from earthquakes with $M_w \gtrsim 5.0$ to emphasize ground motions of engineering significance and to limit analysis to more reliably recorded earthquakes.
- During regression lock magnitudes within ± 0.25 magnitude unit bands centred at halves or integer magnitudes to eliminate errors coming from magnitude determination.
- Note that use of epicentral distance for small earthquakes does not introduce significant bias because dimensions of rupture area of small earthquakes are usually much smaller than distance to recording stations.
- Examine peak ground motions from the small number of normal- (14 records) and reverse-faulting (6 records) earthquakes in set and find that they were not significantly different from ground motions from strike-slip earthquakes (73 records). Therefore combine all data.
- Records mainly from small buildings built as meteorological stations up to three stories tall. Note that this modifies the recorded accelerations and hence increases the uncertainty.
- Exclude data from aftershocks (mainly of the Kocaeli and Duzce earthquakes) because it was from free-field stations and did not want to mix it with the data from the non-free-field records.
- Exclude a few records for which PGA of mainshock is $\lesssim 0.04\,\mathrm{g}$.
- Note that there is limited data and the data is poorly distributed. Also note that there is near-total lack of knowledge of local geology and that some of the records could be affected by the building in which the instrument was housed.
- More than half the records (49 records, 53% of total) are from two $M_w > 7$ earthquakes (Kocaeli and Duzce) so the results are heavily based on the ground motions recorded in these two earthquakes.

2.176 Khademi (2002)

- Ground-motion model is:

$$Y = C_1 \exp(C_2 M)((R + C_3 \exp(C_4 M))^{C_5}) + C_6 S$$

where Y is in g, $C_1 = 0.040311$, $C_2 = 0.417342$, $C_3 = 0.001$, $C_4 = 0.65$, $C_5 = -0.351119$ and $C_6 = -0.035852$ for horizontal PGA and $C_1 = 0.0015$, $C_2 = 0.8548$, $C_3 = 0.001$, $C_4 = 0.4$, $C_5 = -0.463$ and $C_6 = 0.0006$ for vertical PGA.

- Uses two site categories:

$S = 0$ Rock, site categories I and II of Iranian building code.

$S = 1$ Soil, site categories III and IV of Iranian building code.

- Selection criteria are: i) causative earthquake, earthquake fault (if known) and respective parameters are determined with reasonable accuracy, ii) PGA of at least one component $> 50\,\mathrm{gal}$, iii) records from free-field conditions or ground level of low-rise buildings (< three stories), iv) some aftershocks have been eliminated to control effect of a few large earthquakes and v) records have been processed with acceptable filter parameters.
- Regresses directly on Y not on logarithm of Y. Therefore does not calculate standard deviation in normal way. Considers the deviation of individual records from predictive equations as being PGA dependent. Finds that a sigmoidal model fits the data well. Therefore $Y = (ab + cx^d)/(b + x^d)$ where Y is the error term and x is the predicted ground motion, $a = 0.038723$, $b = 0.00207$, $c = 0.29094$ and $d = 4.97132$ for horizontal PGA and $a = 0.00561$, $b = 0.0164$, $c = 0.1648$ and $d = 1.9524$ for vertical PGA.

2.177 Margaris *et al.* (2002a) & Margaris *et al.* (2002b)

- Ground-motion model is:

$$\ln Y = c_0 + c_1 M_w + c_2 \ln(R + R_0) + c_3 S$$

  where Y is in $\mathrm{cm/s^2}$, $c_0 = 4.16$, $c_1 = 0.69$, $c_2 = -1.24$, $R_0 = 6$, $c_3 = 0.12$ and $\sigma = 0.70$.

- Use three site categories:

$S = 0$ NEHRP and UBC category B. 145 records.

$S = 1$ NEHRP and UBC category C. 378 records.

$S = 2$ NEHRP and UBC category D. 221 records.

- Selection criteria are: a) earthquake has $M_w \geq 4.5$, b) $\mathrm{PGA} \geq 0.05\,\mathrm{g}$ and c) $\mathrm{PGA} < 0.05\,\mathrm{g}$ but another record from same earthquake has $\mathrm{PGA} \geq 0.05\,\mathrm{g}$.
- Records mainly from normal faulting earthquakes.
- Exclude data recorded in buildings with four stories or higher.
- Automatically digitize records and process records homogenously, paying special attention to the filters used.
- Correlation between M_w and R in set of records used. For $4.5 \leq M_w \leq 5.0$ records exist at $R \leq 40\,\mathrm{km}$ and for larger magnitudes records exist at intermediate and long distances. For $M_w > 6.0$ there is a lack of records for $R < 20\,\mathrm{km}$.
- Use a two step regression method. In first step use all records to find c_1. In second step use records from earthquakes with $M_w \geq 5.0$ to find c_0, c_2 and c_3.
- Adopt $R_0 = 6\,\mathrm{km}$ because difficult to find R_0 via regression due to its strong correlation with c_2. This corresponds to average focal depth of earthquakes used.
- Also try Ground-motion model: $\ln Y = c'_0 + c'_1 M_w + c'_2 \ln(R^2 + h_0^2)^{1/2} + c'_3 S$. Coefficients are: $c'_0 = 3.52$, $c'_1 = 0.70$, $c'_2 = -1.14$, $h_0 = 7\,\mathrm{km}$ (adopted), $c'_3 = 0.12$ and $\sigma = 0.70$.
- Find no apparent trends in residuals w.r.t. distance.
- Due to distribution of data, equations valid for $5 \leq R \leq 120\,\mathrm{km}$ and $4.5 \leq M_w \leq 7.0$.

2.178 Saini *et al.* (2002)

- Ground-motion model is unknown.

2.179 Schwarz *et al.* (2002)

- Ground-motion model is:

$$\log_{10} a_{H(V)} = c_1 + c_2 M_L + c_4 \log_{10}(r) + c_R S_R + c_A S_A + c_S S_S$$
$$\text{where } r = \sqrt{R_e^2 + h_0^2}$$

  where $a_{H(V)}$ is in g, $c_1 = -3.0815$, $c_2 = 0.5161$, $c_4 = -0.9501$, $c_R = -0.1620$, $c_A = -0.1078$, $c_S = 0.0355$, $h_0 = 2.0$ and $\sigma = 0.3193$ for horizontal PGA and $c_1 = -2.8053$, $c_2 = 0.4858$, $c_4 = -1.1842$, $c_R = -0.1932$, $c_A = -0.0210$, $c_S = 0.0253$, $h_0 = 2.5$ and $\sigma = 0.3247$ for vertical PGA.

- Use three site categories:

  R Rock, subsoil classes A1, (A2) $V_s > 800\,\mathrm{m/s}$ (according to E DIN 4149) or subsoil class B (rock) $760 < V_s \leq 1500\,\mathrm{m/s}$ (according to UBC 97). $S_R = 1$, $S_A = 0$, $S_S = 0$. 59 records.

  A Stiff soil, subsoil classes (A2), B2, C2 $350 \leq V_s \leq 800\,\mathrm{m/s}$ (according to E DIN 4149) or subsoil class C (very dense soil and soft rock) $360 < V_s \leq 760\,\mathrm{m/s}$ (according to UBC 97). $S_A = 1$, $S_R = 0$, $S_S = 0$. 88 records.

  S Soft soil, subsoil classes A3, B3, C3 $V_s < 350\,\mathrm{m/s}$ (according to E DIN 4149) or subsoil class D (stiff clays and sandy soils) $180 < V_s \leq 360\,\mathrm{m/s}$ (according to UBC 97). $S_S = 1$, $S_R = 0$, $S_A = 0$. 536 records.

  KOERI stations classified using UBC 97 and temporary stations of German TaskForce classified using new German code E DIN 4149. Classify temporary stations of German TaskForce using microtremor H/V spectral ratio measurements by comparing shapes of H/V spectral ratios from microtremors to theoretical H/V spectral ratios as well as with theoretical transfer functions determined for idealized subsoil profiles.

- Use Kocaeli aftershock records from temporary German TaskForce stations (records from earthquakes with $1 \lesssim M_L < 4.9$ and distances $R_e < 70\,\mathrm{km}$, 538 records) and from mainshock and aftershocks records from Kandilli Observatory (KOERI) stations ($4.8 \leq M_L \leq 7.2$ and distances $10 \leq R_e \leq 250\,\mathrm{km}$, 145 records).

- Visually inspect all time-histories and only use those thought to be of sufficiently good quality.

- Baseline correct all records.

- Use technique of Ambraseys *et al.* (1996) to find the site coefficients c_R, c_A and c_S, i.e. use residuals from regression without considering site classification.

- Note that equations may not be reliable for rock and stiff soil sites due to the lack of data and that equations probably only apply for $2 \leq M_L \leq 5$ due to lack of data from large magnitude earthquakes.

2.180 Stamatovska (2002)

- Ground-motion model is:

$$\ln \mathrm{PGA} = b' + b_M M + b_R \ln \left\{ \left[\left(\frac{R_e}{\rho} \right)^2 + h^2 \right]^{1/2} + C \right\}$$

  where PGA is in $\mathrm{cm/s^2}$. For Bucharest azimuth $b' = -0.21056$, $b_M = 1.29099$, $b_R = -0.80404$, $C = 40$ and $\sigma = 0.52385$, for Valeni azimuth $b' = -1.52412$, $b_M = 1.42459$, $b_R = -0.70275$, $C = 40$ and $\sigma = 0.51389$ and for Cherna Voda $b' = 4.16765$, $b_M = 1.11724$, $b_R = -1.44067$, $C = 40$ and $\sigma = 0.47607$.

- Focal depths, h, between 89 and 131 km.

- Incomplete data on local site conditions so not included in study.

- Some strong-motion records are not from free-field locations.

- Uses ρ to characterise the non-homogeneity of region. Includes effect of instrument location w.r.t. the main direction of propagation of seismic energy, as well as the non-homogeneous attenuation in two orthogonal directions. $\rho = \sqrt{(1 + tg^2\alpha)/(a^{-2} + tg^2\alpha)}$ where α is angle between instrument and main direction of seismic energy or direction of fault projection on surface and a is parameter defining the non-homogeneous attenuation in two orthogonal directions, or relation between the semi-axes of the ellipse of seismic field.

- Uses a two step method. In first step derive equations for each earthquake using $\ln \mathrm{PGA} = b_0' + b_1 \ln(R_e/\rho)$. In the second step the complete Ground-motion model is found by normalizing separately for each earthquake with a value of ρ defined for that earthquake according to the location for which the equation was defined.

- Notes that there is limited data so coefficients could be unreliable.

- Strong-motion records processed by different institutions.

2.181 Tromans & Bommer (2002)

- Ground-motion model is:

$$\log y = C_1 + C_2 M_s + C_4 \log r + C_A S_A + C_S S_S$$
$$\text{where } r = \sqrt{d^2 + h_0^2}$$

  where y is in $\mathrm{cm/s^2}$, $C_1 = 2.080$, $C_2 = 0.214$, $h_0 = 7.27$, $C_4 = -1.049$, $C_A = 0.058$, $C_S = 0.085$ and $\sigma = 0.27$.

- Use three site categories:

  S Soft soil, $V_{s,30} \leq 360\,\mathrm{m/s}$. $S_S = 1$, $S_A = 0$. 25% of records.

  A Stiff soil, $360 < V_{s,30} < 750\,\mathrm{m/s}$. $S_A = 1$, $S_S = 0$. 50% of records.

  R Rock, $V_{s,30} \geq 750\,\mathrm{m/s}$. $S_S = 0$, $S_A = 0$. 25% of records.

  If no $V_{s,30}$ measurements at station then use agency classifications.

- Supplement dataset of Bommer *et al.* (1998) with 66 new records using same selection criteria as Bommer *et al.* (1998) with a lower magnitude limit of $M_s = 5.5$. Remove 3 records from Bommer *et al.* (1998) with no site classifications.
- Roughly uniform distribution of records w.r.t. magnitude and distance. New data contributes significantly to large magnitude and near-field ranges.
- Correct records using an elliptical filter selecting an appropriate low-frequency cut-off, f_L, individually for each record using the criterion of Bommer *et al.* (1998).
- Plot PGA against f_L for two pairs of horizontal components of ground motion from the BOL and DZC stations from the Duzce earthquake (12/11/1999). Record from BOL was recorded on a GSR-16 digital accelerograph and that from DZC was recorded on a SMA-1 analogue accelerograph. Find PGA is stable for low-frequency cut-offs up to at least $0.4\,\mathrm{Hz}$ for the selected records.

2.182 Zonno & Montaldo (2002)

- Ground-motion model is:

$$\log_{10}(Y) = a + bM + c\log_{10}(R^2 + h^2)^{1/2} + e\Gamma$$

  where Y is in g, $a = -1.632$, $b = 0.304$, $c = -1$, $h = 2.7$, $e = 0$ and $\sigma = 0.275$.

- Use two site categories:

  Soil $V_{s,30} \leq 750\,\mathrm{m/s}$, $\Gamma = 0$.

  Rock $V_{s,30} > 750\,\mathrm{m/s}$, $\Gamma = 1$.

- Note that amount of data available for the Umbria-Marche area in central Italy is sufficiently large to perform statistical analysis at regional scale.
- Focal depths between 2 and $8.7\,\mathrm{km}$. Exclude data from an earthquake that occurred at $47\,\mathrm{km}$.
- Select only records from earthquakes with $M_L \geq 4.5$ recorded at less than $100\,\mathrm{km}$.
- Exclude data from Nocera Umbra station because it shows a strong amplification effect due to the presence of a sub-vertical fault and to highly fractured rocks.
- Uniformly process records using BAP (Basic strong-motion Accelerogram Processing software). Instrument correct records and band-pass filter records using a high-cut filter between 23 and $28\,\mathrm{Hz}$ and a bi-directional Butterworth low-cut filter with corner frequency of $0.4\,\mathrm{Hz}$ and rolloff parameter of 2.
- Note that can use M_L because it does not saturate until about 6.5 and largest earthquake in set is $M_L = 5.9$.
- More than half of records are from earthquakes with $M_L \leq 5.5$.
- State that equations should not be used for $M_L > 6$ because of lack of data.
- Use similar regression method as Ambraseys *et al.* (1996) to find site coefficient, e.

2.183 Alarcón (2003)

- Ground-motion model is (his model 2):

$$\log(a) = A + BM + Cr + D\log(r)$$

where a is in gal, $A = 5.5766$, $B = 0.06052$, $C = 0.0039232$, $D = -2.524849$ and $\sigma = 0.2597$.

- Due to lack of information classify stations as soil or rock (stations with $\leq 10\,\mathrm{m}$ of soil). Only derives equation for rock.
- Uses data from National Accelerometer Network managed by INGEOMINAS from 1993 to 1999.
- Exclude data from subduction zone, focal depths $h > 60\,\mathrm{km}$.
- Focal depths, $11.4 \leq h \leq 59.8\,\mathrm{km}$.
- Exclude data from earthquakes with $M_L < 4.0$.
- Exclude data with $\mathrm{PGA} < 5\,\mathrm{gal}$. $5 \leq \mathrm{PGA} \leq 100.1\,\mathrm{gal}$.
- Derive equations using four different models:

$$\begin{aligned} a &= C_1 e^{C_2 M}(R + C_3)^{-C_4} \\ \log(a) &= A + BM + Cr + D\log(r) \\ \log(y) &= C_0 + C_1(M-6) + C_2(M-6) + C_3\log(r) + C_4 r \\ \ln(a) &= a + bM + d\ln(R) + qh \end{aligned}$$

2.184 Alchalbi *et al.* (2003)

- Ground-motion model is:

$$\log A = b_0 + b_1 M_c + b_r \log r$$

where A is in g, $b_0 = -1.939$, $b_1 = 0.278$, $b_2 = -0.858$ and $\sigma = 0.259$ for horizontal PGA and $b_0 = -2.367$, $b_1 = 0.244$, $b_2 = -0.752$ and $\sigma = 0.264$ for vertical PGA.

- Use two site categories: bedrock ($S = 0$) and sediments ($S = 1$) but found the coefficient b_3 in the term $+b_3 S$ is close to zero so repeat analysis constraining b_3 to 0.
- Records from SSA-1 instruments.
- Carefully inspect and select records.
- Do not use record from the Aqaba ($M = 7.2$) earthquake because it is very far and was only recorded at one station.
- Do not use records from buildings or dams because they are affected by response of structure.
- Instrument correct records. Apply bandpass filter (0.1 to $25\,\mathrm{Hz}$) to some low-quality records.

- Do regression using only records from earthquakes with $4.8 \leq M \leq 5.8$ and also using only records from earthquakes with $3.5 \leq M \leq 4.5$.
- Most data from $M \leq 5$ and $r \leq 100\,\mathrm{km}$.
- Note that use a small set of records and so difficult to judge reliability of derived equation.

2.185 Atkinson & Boore (2003)

- Ground-motion model is:

$$\begin{aligned}
\log Y &= c_1 + c_2\mathbf{M} + c_3 h + c_4 R - g\log R + c_5 \mathrm{sl} S_C + c_6 \mathrm{sl} S_D + c_7 \mathrm{sl} S_E \\
\text{where } R &= \sqrt{D_{\mathrm{fault}}^2 + \Delta^2} \\
\Delta &= 0.00724\, 10^{0.507\mathbf{M}} \\
\mathrm{sl} &= \begin{cases} 1 & \text{for } \mathrm{PGA}_{rx} \leq 100\,\mathrm{cm/s or} f \leq 1\,\mathrm{Hz} \\ 1 - \frac{(f-1)(\mathrm{PGA}_{rx}-100)}{400} & \text{for } 100 < \mathrm{PGArx} < 500\,\mathrm{cm/s}\&1\,\mathrm{Hz} < f < 2\,\mathrm{Hz} \\ 1-(f-1) & \text{for } \mathrm{PGA}_{rx} \geq 500\,\mathrm{cm/s}\&1\,\mathrm{Hz} < f < 2\,\mathrm{Hz} \\ 1 - \frac{\mathrm{PGA}_{rx}-100}{400} & \text{for } 100 < \mathrm{PGArx} < 500\,\mathrm{cm/s}\&f \geq 2\,\mathrm{Hz} \\ 0 & \text{for } \mathrm{PGA}_{rx} \geq 500\,\mathrm{cm/s}\&f \geq 2\,\mathrm{Hz}) \end{cases}
\end{aligned}$$

  where Y is in $\mathrm{cm/s^2}$, f is frequency of interest, PGA_{rx} is predicted PGA on NEHRP B sites, $c_1 = 2.991$, $c_2 = 0.03525$, $c_3 = 0.00759$, $c_4 = -0.00206$, $\sigma_1 = 0.20$ (intra-event) and $\sigma_2 = 0.11$ (inter-event) for interface events and $c_1 = -0.04713$, $c_2 = 0.6909$, $c_3 = 0.01130$, $c_4 = -0.00202$, $\sigma_1 = 0.23$ and $\sigma_2 = 0.14$ for in-slab events and $c_5 = 0.19$, $c_6 = 0.24$, $c_7 = 0.29$ for all events. $g = 10^{1.2-0.18\mathbf{M}}$ for interface events and $g = 10^{0.301-0.01\mathbf{M}}$ for in-slab events. Recommended revised c_1 for interface events in Cascadia is 2.79 and in Japan 3.14, recommended revised c_1 for in-slab events in Cascadia is -0.25 and in Japan 0.10.

- Use four site categories:

  B NEHRP site class B, $V_{s,30} > 760\,\mathrm{m/s}$. $S_C = 0$, $S_D = 0$ and $S_E = 0$.

  C NEHRP site class C, $360 < V_{s,30} \leq 760\,\mathrm{m/s}$. $S_C = 1$, $S_D = 0$ and $S_E = 0$.

  D NEHRP site class D, $180 \leq V_{s,30} \leq 360\,\mathrm{m/s}$. $S_D = 1$, $S_C = 0$ and $S_E = 0$.

  E NEHRP site class E, $V_{s,30} < 180\,\mathrm{m/s}$. $S_E = 1$, $S_C = 0$ and $S_D = 0$.

  Stations in KNET were classified using shear-wave velocity profiles using an statistical method to extrapolate measured shear-wave velocities to depths up to 10–$20\,\mathrm{m}$ to $30\,\mathrm{m}$. Stations in Guerrero array assumed to be on rock, i.e. site class B. Broadband stations in Washington and British Columbia sited on rock ($V_{s,30} \approx 1100\,\mathrm{m/s}$), i.e. site class B. Strong-motion stations in Washington classified using map of site classes based on correlations between geology and $V_{s,30}$ in Washington, and verified at 8 stations using actual borehole measurements. Converted Youngs *et al.* (1997) Geomatrix classifications by assuming Geomatrix A=NEHRP B, Geomatrix B=NEHRP C, Geomatrix C/D=NEHRP D and Geomatrix E=NEHRP E using shear-wave velocity and descriptions of Geomatrix classification.

- Note that cannot develop equations using only Cascadia data because not enough data. Combine data of Crouse (1991) and Youngs *et al.* (1997) with additional data from Cascadia (strong-motion and broadband seismographic records), Japan (KNET data), Mexico (Guerrero array data) and El Salvador data.

- Classify event by type using focal depth and mechanism as:

  In-slab All earthquakes with normal mechanism. Earthquakes with thrust mechanism at depths $> 50\,\mathrm{km}$ or if occur on steeply dipping planes.

  Interface Earthquakes with thrust mechanism at depths $< 50\,\mathrm{km}$ on shallow dipping planes.

  Exclude events of unknown type.

- Exclude events with focal depth $h > 100\,\mathrm{km}$.
- Exclude events that occurred within crust above subduction zones.
- Use many thousands of extra records to explore various aspects of ground motion scaling with M and D_{fault}.
- Data relatively plentiful in most important M-D_{fault} ranges, defined according to deaggregations of typical hazard results. These are in-slab earthquakes of $6.5 \leq \mathbf{M} \leq 7.5$ for $40 \leq D_{\mathrm{fault}} \leq 100\,\mathrm{km}$ and interface earthquakes of $\mathbf{M} \geq 7.5$ for $20 \leq D_{\mathrm{fault}} \leq 200\,\mathrm{km}$.
- Data from KNET from moderate events at large distances are not reliable at higher frequencies due to instrumentation limitations so exclude KNET data from $\mathbf{M} < 6$ at $D_{\mathrm{fault}} > 100\,\mathrm{km}$ and for $\mathrm{M} \geq 6$ at $D_{\mathrm{fault}} > 200\,\mathrm{km}$. Excluded data may be reliable at low frequencies.
- Estimate D_{fault} for data from Crouse (1991) and for recent data using fault length versus $\mathbf{M}$ relations of Wells & Coppersmith (1994) to estimate size of fault plane and assuming epicentre lies above geometric centre of dipping fault plane. Verified estimates for several large events for which fault geometry is known.
- Perform separate regressions for interface and in-slab events because analyses indicated extensive differences in amplitudes, scaling and attenuation between two types.
- Experiment with a variety of functional forms. Selected functional form allows for magnitude dependence of geometrical spreading coefficient, g; the observed scaling with magnitude and amplitude-dependent soil nonlinearity.
- For $h > 100\,\mathrm{km}$ use $h = 100\,\mathrm{km}$ to prevent prediction of unrealistically large amplitudes for deeper earthquakes.
- R is approximately equal to average distance to fault surface. Δ is defined from basic fault-to-site geometry. For a fault with length and width given by equations of Wells & Coppersmith (1994), the average distance to the fault for a specified D_{fault} is calculated (arithmetically averaged from a number of points distributed around the fault), then used to determine Δ. Magnitude dependence of R arises because large events have a large spatial extent, so that even near-fault observation points are far from most of the fault. Coefficients in Δ were defined analytically, so as to represent average fault distance, not be regression. Although coefficients in Δ were varied over a wide range but did not improve accuracy of model predictions.
- Determine magnitude dependence of g by preliminary regressions of data for both interface and in-slab events. Split data into 1 magnitude unit increments to determine slope of attenuation as a function of magnitude using only 1 and $2\,\mathrm{s}$ data and records with $50 \leq D_{\mathrm{fault}} \leq 300\,\mathrm{km}$ ($50\,\mathrm{km}$ limit chosen to avoid near-source distance saturation effects). Within each bin regression was made to a simple functional form:

$\log Y' = a_1 + a_2\mathbf{M} - g\log R + a_3S$ where $Y' = Y\exp(0.001R)$, i.e. Y corrected for curvature due to anelasticity, and $S = 0$ for NEHRP A or B and 1 otherwise. g is far-field slope determined for each magnitude bin.

- Nonlinear soil effects not strongly apparent in database on upon examination of residuals from preliminary regressions, as most records have $\mathrm{PGA} < 200\,\mathrm{cm/s^2}$, but may be important for large M and small D_{fault}. To determine linear soil effects perform separate preliminary regressions for each type of event to determine c_5, c_6 and c_7 assuming linear response. Smooth these results (weighted by number of observations in each subset) to fix c_5, c_6 and c_7 (independent of earthquake type) for subsequent regressions. sl was assigned by looking at residual plots and from consideration of NEHRP guidelines. Conclude that there is weak evidence for records with $\mathrm{PGA}_{rx} > 100\,\mathrm{cm/s^2}$, for NEHRP E sites at periods $< 1\,\mathrm{s}$. Use these observations to fix sl for final regression.

- Final regression needs to be iterated until convergence because of use of PGA_{rx} in definition of dependent variable.

- To optimize fit for M-D_{fault} range of engineering interest limit final regression to data within: $5.5 \leq \mathbf{M} < 6.5$ and $D_{\mathrm{fault}} \leq 80\,\mathrm{km}$, $6.5 \leq \mathbf{M} < 7.5$ and $D_{\mathrm{fault}} \leq 150\,\mathrm{km}$ and $\mathbf{M} \geq 7.5$ and $D \leq 300\,\mathrm{km}$ for interface events and $6.0 \leq \mathbf{M} < 6.5$ and $D_{\mathrm{fault}} \leq 100\,\mathrm{km}$ and $\mathbf{M} \geq 6.5$ and $D_{\mathrm{fault}} \leq 200\,\mathrm{km}$ for in-slab events. These criteria refined by experimentation until achieved an optimal fit for events that are important for seismic hazard analysis. Need to restrict M-D_{fault} for regression because set dominated by records from moderate events and from intermediate distances whereas hazard is from large events and close distances.

- Lightly smooth coefficients (using a weighted 3-point scheme) over frequency to get smooth spectral shape and allows for reliable linear interpolation of coefficients for frequencies not explicitly used in regression.

- In initial regressions, use a $\mathbf{M}^2$ term as well as a $\mathbf{M}$ term leading to a better fit over a linear magnitude scaling but lead to a positive sign of the $\mathbf{M}^2$ rather than negative as expected. Therefore to ensure the best fit in the magnitude range that is important for hazard and constrained by data quadratic source terms refit to linear form. Linear model constrained to provide same results in range $7.0 \leq \mathbf{M} \leq 8.0$ for interface events and $6.5 \leq \mathbf{M} \leq 7.5$ for in-slab events. To ensure that non-decreasing ground motion amplitudes for large magnitudes: for $\mathbf{M} > 8.5$ use $\mathrm{M} = 8.5$ for interface events and for $\mathbf{M} > 8.0$ use $\mathrm{M} = 8.0$ for in-slab events.

- Calculate σ based on records with $\mathbf{M} \geq 7.2$ and $D_{\mathrm{fault}} \leq 100\,\mathrm{km}$ for interface events and $\mathbf{M} \geq 6.5$ and $D_{\mathrm{fault}} \leq 100\,\mathrm{km}$ for in-slab events. These magnitude ranges selected to obtain the variability applicable for hazard calculations. Do not use KNET data when computing σ because data appear to have greater high-frequency site response than data from same soil class from other regions, due to prevalence of sites in Japan with shallow soil over rock.

- Determine σ_1 using data for several well-recorded large events and determining average value. Then calculate σ_2 assuming $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$.

- Examine residuals w.r.t. D_{fault} using all data from $\mathbf{M} \geq 5.5$ and $D_{\mathrm{fault}} \leq 200\,\mathrm{km}$ and $\mathbf{M} \geq 6.5$ and $D_{\mathrm{fault}} \leq 300\,\mathrm{km}$. Find large variability but average residuals near 0 for $D_{\mathrm{fault}} \leq 100\,\mathrm{km}$.

- Find significantly lower variability for $\mathbf{M} \geq 7.2$ events ($\sigma = 0.2$–0.35 for larger events and $\sigma = 0.25$–0.4 for smaller events).
- Examine graphs and statistics of subsets of data broken down by magnitude, soil type and region. Find significant positive residuals for $\mathbf{M} < 6.6$ due to use of linear scaling with magnitude. Accept positive residuals because small magnitudes do not contribute strongly to hazard.
- Find large positive residuals for class C sites for interface events (most records are from Japan) whereas residuals for class C sites for in-slab events (which are from both Japan and Cascadia) do not show trend. No other overwhelming trends. Differences in residuals for Japan and Cascadia class C sites likely due to differences in typical soil profiles in the two regions within the same NEHRP class. Sites in Japan are typically shallow soil over rock, which tend to amplify high frequencies, whereas in Cascadia most soil sites represent relatively deep layers over rock or till. Provide revised c_1 coefficients for Japan and Cascadia to model these differences.
- Note that debate over whether 1992 Cape Mendocino earthquake is a subduction zone or crustal earthquake. Excluding it from regressions has a minor effect on results, reducing predictions for interface events for $\mathbf{M} < 7.5$.

2.186 Boatwright *et al.* (2003)

- Ground-motion model is:

$$\begin{aligned}
\log \mathrm{PGA} &= \psi(\mathbf{M}) - \log g(r) - \eta'(\mathbf{M}) r \\
\text{where} & \\
\psi(\mathbf{M}) &= \psi_1 + \psi_2(\mathbf{M} - 5.5) \quad \text{for} \quad \mathbf{M} \leq 5.5 \\
&= \psi_1 + \psi_3(\mathbf{M} - 5.5) \quad \text{for} \quad \mathbf{M} > 5.5 \\
\eta'(\mathbf{M}) &= \eta_1 \quad \text{for} \quad \mathbf{M} \leq 5.5 \\
&= \eta_1 \times 10^{\rho(\mathbf{M}-5.5)} \quad \mathbf{M} > 5.5 \\
g(r) &= r \quad \text{for} \quad r \leq r_0 = 27.5\,\mathrm{km} \\
&= r_0 (r/r_0)^{0.7} \quad \text{for} \quad r > r_0 = 27.5\,\mathrm{km}
\end{aligned}$$

where PGA is in $\mathrm{m/s^2}$, $\psi_1 = 1.45 \pm 0.24$, $\psi_2 = 1.00 \pm 0.01$, $\psi_3 = 0.31 \pm 0.09$, $\eta_1 = 0.0073 \pm 0.0003$, $\rho = -0.30 \pm 0.06$, $\sigma_e = 0.170$ (inter-earthquake) and $\sigma_r = 0.361$ (intra-earthquake).

- Classify station into four classes using the NEHRP categories using geological maps:

  B Rock. Amplification from category C 0.79.

  C Soft rock or stiff soil. Amplification from category C 1.00.

  D Soft soil. Amplification from category C 1.35.

  E Bay mud. Amplification from category D 1.64.

  The amplifications (from Boore *et al.* (1997)) are used to correct for site effects.

  For some stations in the broadband Berkeley Digital Seismic Network, which are in seismic vaults and mine adits and therefore have low site amplifications, use one-half the above site amplifications.

- Use data from August 1999 and December 2002 from the northern California ShakeMap set of data. Extend set to larger earthquakes by adding data from nine previous large northern California earthquakes.
- Focal depths, $0.1 \leq h \leq 28..8\,\mathrm{km}$.
- Use hypocentral distance because this distance is available to ShakeMap immediately after an earthquake. Note that this is a poor predictor of near-field ground motion from extended faults.
- Plot decay of PGA with distance for two moderate earthquakes ($\mathbf{M} = 4.9$, $\mathbf{M} = 3.9$) and find decay is poorly fit by a power-law function of distance and that fitting such an equation who require $\mathrm{PGA} \propto r^{-2}$, which they believe is physically unrealistic for body-wave propagation.
- Find that PGAs flatten or even increase at large distances, which is believed to be due to noise. Hence use a magnitude-dependent limit of $r_{\max} = 100(\mathbf{M} - 2) \leq 400\,\mathrm{km}$, determined by inspecting PGA and PGV data for all events, to exclude problem data.
- Fit data from each event separately using $\log \mathrm{PGA} = \psi - \eta r - \log g(r) + \log s_{\mathrm{BJF}}$. Find η varies between four groups: events near Eureka triple junction, events within the Bay Area, events near San Juan Bautista and those in the Sierras and the western Mojave desert.
- Use a numerical search to find the segmentation magnitude $\mathbf{M}'$. Choose $\mathbf{M}' = 5.5$ as the segmentation magnitude because it is the lowest segmentation magnitude within a broad minimum in the χ^2 error for the regression.
- Fit magnitude-dependent part of the equation to the PGA values scaled to $10\,\mathrm{km}$ and site class C.
- Note that the PGAs predicted are significantly higher than those given by equations derived by Joyner & Boore (1981) and Boore *et al.* (1997) because of use of hypocentral rather than fault distance.
- Recompute site amplifications relative to category C as: for B 0.84 ± 0.03, for D 1.35 ± 0.05 and for E 2.17 ± 0.15.

2.187 Bommer *et al.* (2003)

- Ground-motion model is:

$$\log y = C_1 + C_2 M + C_4 \log(\sqrt{r^2 + h^2}) + C_A S_A + C_S S_S + C_N F_N + C_R F_R$$

  where y is in g, $C_1 = -1.482$, $C_2 = 0.264$, $C_4 = -0.883$, $h = 2.473$, $C_A = 0.117$, $C_S = 0.101$, $C_N = -0.088$, $C_R = -0.021$, $\sigma_1 = 0.243$ (intra-event) and $\sigma_2 = 0.060$ (inter-event).

- Use four site conditions but retain three (because only three records from very soft (L) soil which combine with soft (S) soil category):

  R Rock: $V_s > 750\,\mathrm{m/s}$, $\Rightarrow S_A = 0, S_S = 0$, 106 records.

  A Stiff soil: $360 < V_s \leq 750\,\mathrm{m/s}$, $\Rightarrow S_A = 1, S_S = 0$, 226 records.

S Soft soil: $180 < V_s \leq 360\,\mathrm{m/s}$, $\Rightarrow S_A = 0, S_S = 1$, 81 records.

L Very soft soil: $V_s \leq 180\,\mathrm{m/s}$, $\Rightarrow S_A = 0, S_S = 1$, 3 records.

- Use same data as Ambraseys *et al.* (1996).

- Use three faulting mechanism categories:

  S Strike-slip: earthquakes with rake angles (λ) $-30 \leq \lambda \leq 30°$ or $\lambda \geq 150°$ or $\lambda \leq -150°$, $\Rightarrow F_N = 0, F_R = 0$, 47 records.

  N Normal: earthquakes with $-150 < \lambda < -30°$, $\Rightarrow F_N = 1, F_R = 0$, 146 records.

  R Reverse: earthquakes with $30 < \lambda < 150°$, $\Rightarrow F_R = 1, F_N = 0$, 229 records.

  Earthquakes classified as either strike-slip or reverse or strike-slip or normal depending on which plane is the main plane were included in the corresponding dip-slip category. Some records (137 records, 51 normal, 10 strike-slip and 76 reverse) from earthquakes with no published focal mechanism (80 earthquakes) were classified using the mechanism of the mainshock or regional stress characteristics.

- Try using criteria of Campbell (1997) and Sadigh *et al.* (1997) to classify earthquakes w.r.t. faulting mechanism. Also try classifying ambiguously classified earthquakes as strike-slip. Find large differences in the faulting mechanism coefficients with more stricter criteria for the rake angle of strike-slip earthquakes leading to higher C_R coefficients.

- Note that distribution of records is reasonably uniform w.r.t. to mechanism although significantly fewer records from strike-slip earthquakes.

- Try to use two-stage maximum-likelihood method as employed by Ambraseys *et al.* (1996) but find numerical instabilities in regression.

- Also rederive mechanism-independent equation of Ambraseys *et al.* (1996) using one-stage maximum-likelihood method.

2.188 Campbell & Bozorgnia (2003d,a,b,c) & Bozorgnia & Campbell (2004b)

- Ground-motion model is:

$$
\begin{aligned}
\ln Y &= c_1 + f_1(M_w) + c_4 \ln \sqrt{f_2(M_w, r_{\text{seis}}, S)} + f_3(F) + f_4(S) \\
&\quad + f_5(\text{HW}, F, M_w, r_{\text{seis}}) \\
\text{where} \quad f_1(M_w) &= c_2 M_w + c_3(8.5 - M_w)^2 \\
f_2(M_w, r_{\text{seis}}, S) &= r_{\text{seis}}^2 + g(S)^2(\exp[c_8 M_w + c_9(8.5 - M_w)^2])^2 \\
g(S) &= c_5 + c_6(S_{VFS} + S_{SR}) + c_7 S_{FR} \\
f_3(F) &= c_{10} F_{RV} + c_{11} F_{TH} \\
f_4(S) &= c_{12} S_{VFS} + c_{13} S_{SR} + c_{14} S_{FR} \\
f_5(\text{HW}, F, M_w, r_{\text{seis}}) &= \text{HW} f_{\text{HW}}(M_w) f_{\text{HW}}(r_{\text{seis}})(F_{\text{RV}} + F_{\text{TH}}) \\
\text{HW} &= \begin{cases} 0 & \text{for} \quad r_{\text{jb}} \geq 5\,\text{km or } \delta > 70^\circ \\ (S_{VFS} + S_{SR} + S_{FR})(5 - r_{\text{jb}})/5 & \text{for} \quad r_{\text{jb}} < 5\,\text{km \& } \delta \leq 70^\circ \end{cases} \\
f_{\text{HW}}(M_w) &= \begin{cases} 0 & \text{for} \quad M_w < 5.5 \\ M_w - 5.5 & \text{for} \quad 5.5 \leq M_w \leq 6.5 \\ 1 & \text{for} \quad M_w > 6.5 \end{cases} \\
f_{\text{HW}}(r_{\text{seis}}) &= \begin{cases} c_{15}(r_{\text{seis}}/8) & \text{for} \quad r_{\text{seis}} < 8\,\text{km} \\ c_{15} & \text{for} \quad r_{\text{seis}} \geq 8\,\text{km} \end{cases}
\end{aligned}
$$

where Y is in g, r_{jb} is the distance to the surface projection of rupture and δ is the dip of the fault; for uncorrected horizontal PGA: $c_1 = -2.896$, $c_2 = 0.812$, $c_3 = 0.0$, $c_4 = -1.318$, $c_5 = 0.187$, $c_6 = -0.029$, $c_7 = -0.064$, $c_8 = 0.616$, $c_9 = 0$, $c_{10} = 0.179$, $c_{11} = 0.307$, $c_{12} = -0.062$, $c_{13} = -0.195$, $c_{14} = -0.320$, $c_{15} = 0.370$ and $\sigma = c_{16} - 0.07M_w$ for $M_w < 7.4$ and $\sigma = c_{16} - 0.518$ for $M_w \geq 7.4$ where $c_{16} = 0.964$ or $\sigma = c_{17} + 0.351$ for $\text{PGA} \leq 0.07\,\text{g}$, $\sigma = c_{17} - 0.132\ln(\text{PGA})$ for $0.07\,\text{g} < \text{PGA} < 0.25\,\text{g}$ and $\sigma = c_{17} + 0.183$ for $\text{PGA} \geq 0.25\,\text{g}$ where $c_{17} = 0.263$; for corrected horizontal PGA: $c_1 = -4.033$, $c_2 = 0.812$, $c_3 = 0.036$, $c_4 = -1.061$, $c_5 = 0.041$, $c_6 = -0.005$, $c_7 = -0.018$, $c_8 = 0.766$, $c_9 = 0.034$, $c_{10} = 0.343$, $c_{11} = 0.351$, $c_{12} = -0.123$, $c_{13} = -0.138$, $c_{14} = -0.289$, $c_{15} = 0.370$ and $\sigma = c_{16} - 0.07M_w$ for $M_w < 7.4$ and $\sigma = c_{16} - 0.518$ for $M_w \geq 7.4$ where $c_{16} = 0.920$ or $\sigma = c_{17} + 0.351$ for $\text{PGA} \leq 0.07\,\text{g}$, $\sigma = c_{17} - 0.132\ln(\text{PGA})$ for $0.07\,\text{g} < \text{PGA} < 0.25\,\text{g}$ and $\sigma = c_{17} + 0.183$ for $\text{PGA} \geq 0.25\,\text{g}$ where $c_{17} = 0.219$; for uncorrected vertical PGA: $c_1 = -2.807$, $c_2 = 0.756$, $c_3 = 0$, $c_4 = -1.391$, $c_5 = 0.191$, $c_6 = 0.044$, $c_7 = -0.014$, $c_8 = 0.544$, $c_9 = 0$, $c_{10} = 0.091$, $c_{11} = 0.223$, $c_{12} = -0.096$, $c_{13} = -0.212$, $c_{14} = -0.199$, $c_{15} = 0.630$ and $\sigma = c_{16} - 0.07M_w$ for $M_w < 7.4$ and $\sigma = c_{16} - 0.518$ for $M_w \geq 7.4$ where $c_{16} = 1.003$ or $\sigma = c_{17} + 0.351$ for $\text{PGA} \leq 0.07\,\text{g}$, $\sigma = c_{17} - 0.132\ln(\text{PGA})$ for $0.07\,\text{g} < \text{PGA} < 0.25\,\text{g}$ and $\sigma = c_{17} + 0.183$ for $\text{PGA} \geq 0.25\,\text{g}$ where $c_{17} = 0.302$; and for corrected vertical PGA: $c_1 = -3.108$, $c_2 = 0.756$, $c_3 = 0$, $c_4 = -1.287$, $c_5 = 0.142$, $c_6 = 0.046$, $c_7 = -0.040$, $c_8 = 0.587$, $c_9 = 0$, $c_{10} = 0.253$, $c_{11} = 0.173$, $c_{12} = -0.135$, $c_{13} = -0.138$, $c_{14} = -0.256$, $c_{15} = 0.630$ and $\sigma = c_{16} - 0.07M_w$ for $M_w < 7.4$ and $\sigma = c_{16} - 0.518$ for $M_w \geq 7.4$ where $c_{16} = 0.975$ or $\sigma = c_{17} + 0.351$ for $\text{PGA} \leq 0.07\,\text{g}$, $\sigma = c_{17} - 0.132\ln(\text{PGA})$ for $0.07\,\text{g} < \text{PGA} < 0.25\,\text{g}$ and $\sigma = c_{17} + 0.183$ for $\text{PGA} \geq 0.25\,\text{g}$ where $c_{17} = 0.274$.

- Use four site categories:

Firm soil Generally includes soil deposits of Holocene age (less than 11,000 years old) described on geological maps as recent alluvium, alluvial fans, or undifferentiated Quaternary deposits. Approximately corresponds to $V_{s,30} = 298 \pm 92\,\mathrm{m/s}$ and NEHRP soil class D. Uncorrected PGA: 534 horizontal records and 525 vertical records and corrected PGA: 241 horizontal records and 240 vertical records. $S_{VFS} = 0$, $S_{SR} = 0$ and $S_{FR} = 0$.

Very firm soil Generally includes soil deposits of Pleistocene age (11,000 to 1.5 million years old) described on geological maps as older alluvium or terrace deposits. Approximately corresponds to $V_{s,30} = 368 \pm 80\,\mathrm{m/s}$ and NEHRP soil class CD. Uncorrected PGA: 168 horizontal records and 166 vertical records and corrected PGA: 84 horizontal records and 83 vertical records. $S_{VFS} = 1$, $S_{SR} = 0$ and $S_{FR} = 0$.

Soft rock Generally includes sedimentary rock and soft volcanic deposits of Tertiary age (1.5 to 100 million years old) as well as 'softer' units of the Franciscan Complex and other low-grade metamorphic rocks generally described as melange, serpentine and schist. Approximately corresponds to $V_{s,30} = 421 \pm 109\,\mathrm{m/s}$ and NEHRP soil class CD. Uncorrected PGA: 126 horizontal records and 124 vertical records and corrected PGA: 63 horizontal records and 62 vertical records. $S_{SR} = 1$, $S_{VFS} = 0$ and $S_{FR} = 0$.

Firm rock Generally include older sedimentary rocks and hard volcanic deposits, high-grade metamorphic rock, crystalline rock and the 'harder' units of the Franciscan Complex generally described as sandstone, greywacke, shale, chert and greenstone. Approximately corresponds to $V_{s,30} = 830 \pm 339\,\mathrm{m/s}$ and NEHRP soil class BC. Uncorrected PGA: 132 horizontal records and 126 vertical records and corrected PGA: 55 horizontal records and 54 vertical records. $S_{FR} = 1$, $S_{VFS} = 0$ and $S_{SR} = 0$.

Note that for generic soil (approximately corresponding to $V_{s,30} = 310\,\mathrm{m/s}$ and NEHRP site class D) use $S_{VFS} = 0.25$, $S_{SR} = 0$, $S_{FR} = 0$ and for generic rock (approximately corresponding to $V_{s,30} = 620\,\mathrm{m/s}$ and NEHRP site class C) use $S_{SR} = 0.50$, $S_{FR} = 0.50$ and $S_{VFS} = 0$.

- Use four fault types but only model differences between strike-slip, reverse and thrust:

Normal Earthquakes with rake angles between $202.5°$ and $337.5°$. 4 records from 1 earthquake.

Strike-slip Includes earthquakes on vertical or near-vertical faults with rake angles within $22.5°$ of the strike of the fault. Also include 4 records from 1975 Oroville normal faulting earthquake. Uncorrected PGA: 404 horizontal records and 395 vertical records and corrected PGA: 127 horizontal and vertical records. $F_{RV} = 0$ and $F_{TH} = 0$

Reverse Steeply dipping earthquakes with rake angles between $22.5°$ and $157.5°$. Uncorrected PGA: 186 horizontal records and 183 vertical records and corrected PGA: 58 horizontal records and 57 vertical records. $F_{RV} = 1$ and $F_{TH} = 0$.

Thrust Shallow dipping earthquakes with rake angles between $22.5°$ and $157.5°$. Includes some blind thrust earthquakes. Uncorrected PGA: 370 horizontal records and 363 vertical records and corrected PGA: 258 horizontal records and 255 vertical records. $F_{TH} = 1$ and $F_{RV} = 0$.

Note that for generic (unknown) fault type use $F_{RV} = 0.25$ and $F_{TH} = 0.25$.

- Most records from $5.5 \leq M_w \leq 7.0$.

- Note that equations are an update to equations in Campbell (1997) because they used a somewhat awkward and complicated set of Ground-motion models because there used a mixture of functional forms. Consider that the new equations supersede their previous studies.
- Uncorrected PGA refers to the standard level of accelerogram processing known as Phase 1. Uncorrected PGAs are either scaled directly from the recorded accelerogram or if the accelerogram was processed, from the baseline and instrument-corrected Phase 1 acceleration time-history.
- Corrected PGA measured from the Phase 1 acceleration time-history after it had been band-pass filtered and decimated to a uniform time interval.
- Restrict data to within $60\,\mathrm{km}$ of seismogenic rupture zone ($r_{\mathrm{seis}} \leq 60\,\mathrm{km}$) of shallow crustal earthquakes in active tectonic regions which have source and near-source attenuation similar to California. Most data from California with some from Alaska, Armenia, Canada, Hawaii, India, Iran, Japan, Mexico, Nicaragua, Turkey and Uzbekistan. Note some controversy whether this is true for all earthquakes (e.g. Gazli and Nahanni). Exclude subduction-interface earthquakes.
- Restrict earthquakes to those with focal depths $< 25\,\mathrm{km}$.
- Exclude data from subduction-interface earthquakes, since such events occur in an entirely different tectonic environment that the other shallow crustal earthquakes, and it has not been clearly shown that their near-source ground motions are similar to those from shallow crustal earthquakes.
- Restrict to $r_{\mathrm{seis}} \leq 60\,\mathrm{km}$ to avoid complications related to the arrival of multiple reflections from the lower crust. Think that this distance range includes most ground-motion amplitudes of engineering interest.
- All records from free-field, which define as instrument shelters or non-embedded buildings < 3 storeys high and < 7 storeys high if located on firm rock. Include records from dam abutments to enhance the rock records even though there could be some interaction between dam and recording site. Exclude records from toe or base of dam because of soil-structure interaction.
- Do preliminary analysis, find coefficients in f_3 need to be constrained in order to make Y independent on M_w at $r_{\mathrm{seis}} = 0$, otherwise Y exhibits ‘oversaturation’ and decreases with magnitude at close distances. Therefore set $c_8 = -c_2/c_4$ and $c_9 = -c_3/c_4$.
- Functional form permits nonlinear soil behaviour.
- Do not include sediment depth (depth to basement rock) as a parameter even though analysis of residuals indicated that it is an important parameter especially at long periods. Do not think its exclusion is a serious practical limitation because sediment depth is generally not used in engineering analyses and not included in any other widely used attenuation relation.
- Do not apply weights during regression analysis because of the relatively uniform distribution of records w.r.t. magnitude and distance.
- To make regression analysis of corrected PGA more stable set c_2 equal to value from better-constrained regression of uncorrected PGAs.

- Examine normalised residuals $\delta_i = (\ln Y_i - \ln \bar{Y})/\sigma_{\ln(\mathrm{Unc.PGA}}$ where $\ln Y_i$ is the measured acceleration, $\bar{Y}$ is the predicted acceleration and $\sigma_{\ln(\mathrm{Unc.PGA}}$ is the standard deviation of the uncorrected PGA equation. Plot δ_i against magnitude and distance and find models are unbiased.
- Consider equations valid for $M_w \geq 5.0$ and $r_{\mathrm{seis}} \leq 60\,\mathrm{km}$. Probably can be extrapolated to a distance of $100\,\mathrm{km}$ without serious compromise.
- Note that should use equations for uncorrected PGA if only an estimate of PGA is required because of its statistical robustness. If want response spectra and PGA then should use corrected PGA equation because the estimates are then consistent.
- Note that should include ground motions from Kocaeli (17/8/1999, $M_w = 7.4$), Chi-Chi (21/9/1999, $M_w = 7.6$), Hector Mine (16/10/1999, $M_w = 7.1$) and Duzce (12/11/1999, $M_w = 7.1$) earthquakes but because short-period motions from these earthquakes was significantly lower than expected their inclusion could lead to unconservative estimated ground motions for high magnitudes.
- Prefer the relationship for σ in terms of PGA because statistically more robust. Note that very few records to constrain value of σ for large earthquakes but many records to constrain σ for $\mathrm{PGA} \geq 0.25\,\mathrm{g}$.
- Find that Monte Carlo simulation indicates that all regression coefficients statistically significant at 10% level.

2.189 Halldórsson & Sveinsson (2003)

- Ground-motion models are:

$$\log A = aM - b\log R + c$$

where A is in g, $a = 0.484$, $b = 1.4989$, $c = -2.1640$ and $\sigma = 0.3091$, and:

$$\log A = aM - \log R - bR + c$$

$a = 0.4805$, $b = 0.0049$, $c = -2.6860$ and $\sigma = 0.3415$.

- Vast majority of data from south Iceland (18 earthquakes in SW Iceland and 4 in N Iceland).
- Most data from less than $50\,\mathrm{km}$ and $M < 5.5$. 76% of data is from 5 to $50\,\mathrm{km}$.
- Examine residual plots against distance and find no trends.
- Recommend first equation.
- Most data from five earthquakes (04/06/1998, 13/11/1998, 27/09/1999, 17/06/2000 and 21/06/2000).

2.190 Shi & Shen (2003)

- Ground-motion model is:

$$\log \mathrm{PGA} = a_1 + a_2 M_s + a_3 \log[R + a_4 \exp(a_5 M_s)]$$

where PGA is in $\mathrm{cm/s^2}$, $a_1 = 1.3012$, $a_2 = 0.6057$, $a_3 = -1.7216$, $a_4 = 1.126$ and $a_5 = 0.482$ (σ not reported).

2.191 Sigbjörnsson & Ambraseys (2003)

- Ground-motion model is:

$$\log_{10}(\mathrm{PGA}) = b_0 + b_1 M - \log_{10}(R) + b_2 R$$
$$R = \sqrt{D^2 + h^2}$$

where PGA is in g, $b_0 = -1.2780 \pm 0.1909$, $b_1 = 0.2853 \pm 0.0316$, $b_2 = -1.730 \times 10^{-3} \pm 2.132 \times 10^{-4}$ and $\sigma = 0.3368$ ($\pm$ indicates the standard deviation of the coefficients). h was fixed arbitrarily to $8\,\mathrm{km}$.

- Use data from ISESD (Ambraseys *et al.* , 2004). Select using $d_e < 1000\,\mathrm{km}$, $5 \leq M \leq 7$ (where M is either M_w or M_s).
- Focal depths $< 20\,\mathrm{km}$.
- Only use data from strike-slip earthquakes.
- Note that coefficient of variation for b coefficients is in range 11 to 15%.
- Note that b_0 and b_1 are very strongly negatively correlated (correlation coefficient of -0.9938), believed to be because PGA is governed by $b_0 + b_1 M$ as D approaches zero, but they are almost uncorrelated with b_2 (correlation coefficients of -0.0679 and -0.0076 for b_0 and b_1 respectively), believed to be because of zero correlation between M and D in the data used.
- Also derive equation using $\log_{10}(\mathrm{PGA}) = b_0 + b_1 M + b_2 R + b_3 \log_{10}(R)$ (do not report coefficients) and find slightly smaller residuals but similar behaviour of the b parameters.
- Plot distribution of residuals (binned into intervals of 0.25 units) and the normal probability density function.

2.192 Skarlatoudis *et al.* (2003)

- Ground-motion model is:

$$\log Y = c_0 + c_1 M + c_2 \log(R^2 + h^2)^{1/2} + c_3 F + c_5 S$$

where Y is in $\mathrm{cm/s^2}$, $c_0 = 0.86$, $c_1 = 0.45$, $c_2 = -1.27$, $c_3 = 0.10$, $c_5 = 0.06$ and $\sigma = 0.286$.

- Use three site classes (from NEHRP):

$S = 0$ B: 19 stations plus 6 stations between A and B

$S = 1$ C: 68 stations

$S = 2$ D: 25 stations

No stations in NEHRP class A or E. Use geotechnical information where available and geological maps for the other stations.

- Focal depths, h, between 0.0 and $30.1\,\mathrm{km}$.
- Classify earthquakes into three faulting mechanism classes:

$F = 0$ Normal, 101 earthquakes

$F = 1$ Strike-slip, 89 earthquakes

$F = 1$ Thrust, 35 earthquakes

but only retain two categories: normal and strike-slip/thrust. Classify using plunges of P and T axes and also knowledge of the geotectonic environment. Have fault-plane solutions for 67 earthquakes.

- Choose data that satisfies at least one of these criteria:
  - from earthquake with $M_w \geq 4.5$;
  - record has PGA $\geq 0.05\,\mathrm{g}$, independent of magnitude;
  - record has PGA $< 0.05\,\mathrm{g}$ but at least one record from earthquake has PGA $\geq 0.05\,\mathrm{g}$.
- Relocate all earthquakes.
- Redigitise all records using a standard procedure and bandpass filter using cut-offs chosen by a comparison of the Fourier amplitude spectrum (FAS) of the record to the FAS of the digitised fixed trace. Find that PGAs from uncorrected and filtered accelerograms are almost identical.
- Convert M_L to M_w, for earthquakes with no M_w, using a locally derived linear equation
- Most data from earthquakes with $M_w < 6$ and $r_{hypo} < 60\,\mathrm{km}$.
- Note correlation in data between M_w and r_{hypo}.
- Note lack of near-field data ($R < 20\,\mathrm{km}$) for $M_w > 6.0$.
- Plot estimated distance at which instruments would not be expected to trigger and find that all data lie within the acceptable distance range for mean trigger level and only 14 records fall outside the distance range for trigger level plus one σ. Try excluding these records and find no effect. Hence conclude that record truncation would not affect results.
- Use an optimization procedure based on the least-squares technique using singular value decomposition because two-step methods always give less precise results than one-step techniques. Adopted method allows the controlling of stability of optimization and accurate determination and analysis of errors in solution. Also method expected to overcome and quantify problems arising from correlation between magnitude and distance.
- Test assumption that site coefficient for site class D is twice that for C by deriving equations with two site terms: one for C and one for D. Find that the site coefficient for D is roughly twice that of site coefficient for C.
- Test effect of focal mechanism by including two coefficients to model difference between normal, strike-slip and thrust motions. Find that the coefficients for difference between strike-slip and normal and between thrust and normal are almost equal. Hence combine strike-slip and thrust categories.
- Try including quadratic M term but find inadmissible (positive) value due to lack of data from large magnitude events.

- Also derive equations using this functional form: $\log Y = c_0 + c_1 M + c_2 \log(R + c_4) + c_3 F + c_5 S$ where c_4 was constrained to $6\,\mathrm{km}$ from an earlier study due to problems in deriving reliable values of c_2 and c_4 directly by regression.
- Plot observed data scaled to $M_w 6.5$ against predictions and find good fit.
- Find no systematic variations in residuals w.r.t. remaining variables.
- Find reduction in σ w.r.t. earlier studies. Relate this to better locations and site classifications.

2.193 Beauducel *et al.* (2004)

- Ground-motion model is:

$$\log(\mathrm{PGA}) = aM + bR - \log(R) + c$$

  where PGA is in g, $a = 0.611377$, $b = -0.00584334$, $c = -3.216674$ and $\sigma = 0.5$.
- Do not include terms for site effects due to uncertainty of site classifications (rock/soil). Suggest multiplying predictions by 3 to estimate PGA at soil sites.
- Derive model to better estimate macroseismic intensities rapidly after an earthquake.
- Select data from 21/11/2004 to 28/12/2004, which mainly come from earthquakes in the Les Saintes sequence but include some subduction events and crustal earthquakes in other locations.
- Data from 13 stations on Guadeloupe.
- Vast majority of data from $M < 4$ and $20 < d < 100\,\mathrm{km}$.
- Remove constant offset from accelerations but do not filter.
- Use resolved maximum because other definitions (e.g. larger) can underestimate PGA by up to 30%.
- Plot residuals against M and find no trends. Observe some residuals of ± 1.5.
- Apply model to other earthquakes from the region and find good match to observations.

2.194 Beyaz (2004)

- Ground-motion model is:

$$\log \mathrm{PGA} = a_1 + a_2 M_w^2 + a_3 \log(r + a_4)$$

  where PGA is in unknown unit (probably $\mathrm{cm/s^2}$), $a_1 = 2.581$, $a_2 = 0.029$, $a_3 = -1.305$, $a_4 = 7$ and $\sigma = 0.712$[8].
- Data from rock sites.

[8] It is stated that common logarithms are used but this standard deviation is extremely high and hence it may actually be in terms of natural logarithms.

2.195 Bragato (2004)

- Ground-motion model is:

$$\log_{10}(y) = a + (b + cm)m + (d + em)\log_{10}(\sqrt{r^2 + h^2})$$

  where y is in g, $a = 0.46$, $b = 0.35$, $c = 0.07$, $d = -4.79$, $e = 0.60$, $h = 8.9\,\mathrm{km}$ and $\sigma = 0.33$.

- Investigates effect of nontriggering stations on derivation of empirical Ground-motion model based on the assumption that the triggering level is known (or can be estimated from data) but do not know which stations triggered (called left truncated data).

- Develops mathematical theory and computational method (after trying various alternative methods) for truncated regression analysis (TRA) and randomly truncated regression analysis (RTRA) (where triggering level changes with time).

- Tests developed methods on 1000 lognormally-distributed synthetic data points simulated using the equation of Ambraseys *et al.* (1996) for $4 \leq M_s \leq 7$ and $1 \leq d_f \leq 100\,\mathrm{km}$. A fixed triggering threshold of $0.02\,\mathrm{g}$ is imposed. Regresses remaining 908 samples using TRA and RTRA. Finds a very similar equation using TRA but large differences for $d_f > 20\,\mathrm{km}$ by using standard regression analysis (SRA) due to slower attenuation. Also apply TRA to randomly truncated synthetic data and find a close match to original curve, which is not found using SRA.

- Applies method to 189 records from rock sites downloaded from ISESD with $M > 4.5$ (scale not specified) and $d < 80\,\mathrm{km}$ (scale not specified) using functional form: $\log_{10}(y) = a + bm + c\log_{10}(\sqrt{r^2 + h^2})$. Uses these selection criteria to allow use of simple functional form and to avoid complications due to crustal reflections that reduce attenuation. Discards the five points with PGA $< 0.01\,\mathrm{g}$ (assumed threshold of SMA-1s). Applies TRA and SRA. Finds both M-scaling and distance attenuation are larger with TRA than with SRA because TRA accounts for larger spread in original (not truncated) data. Differences are relevant for $M < 6$ and $d > 20\,\mathrm{km}$.

- Applies method to dataset including, in addition, non-rock records (456 in total). Finds no differences between TRA and SRA results. Believes that this is due to lack of data in range possibly affected by truncation (small M and large d). Finds similar results to Ambraseys *et al.* (1996).

- Applies method to NE Italian data from seven seismometric and ten accelerometric digital stations assuming: $\log_{10}(y) = a + bm + c\log_{10}(\sqrt{r^2 + h^2})$. Accelerometric stations used usually trigger at $0.001\,\mathrm{g}$. Seismometric stations used trigger based on ratio of short-term and long-term averages (STA/LTA), which varies from station to station and acts like a random threshold. Firstly neglects randomness and assumes trigger level of each station equals lowest recorded PGA and applies TRA and SRA. Finds small differences for $d < 8\,\mathrm{km}$ and $d > 30\,\mathrm{km}$.

- Applies method using functional form above, which believes is more physically justified. SRA does not converge. Studies reason for this by regressing on data from M intervals of 0.3 units wide. Finds behaviour of PGAs inverts for $M < 3$. Finds increasing σ with decreasing M for $M > 3$. TRA does converge and shows stronger magnitude saturation than SRA.

- Notes that application of RTRA to model effect of STA/LTA for used data is not realistic since probably not enough data to constrain all 23 parameters and to computational expensive using adopted maximization technique for RTRA.
- Estimates the random truncation parameters for one station (Zoufplan) and finds that the fixed threshold assumption made is acceptable since estimated random truncation parameters predict that only 14% of observations are lost at the earlier assumed fixed threshold level (the lowest PGA recorded).

2.196 Gupta & Gupta (2004)

- Ground-motion model is:

$$\ln \mathrm{PGA} = C_1 + C_2 M + C_3 \ln R_h + C_4 R_h + C_5 v$$

  where PGA is in g, $C_1 = -7.515$, $C_2 = 1.049$, $C_3 = -0.105$, $C_4 = -0.0211$, $C_5 = -0.287$ and $\sigma = 0.511$. $v = 0$ for horizontal PGA and 1 for vertical PGA.
- Data from basalt sites (7 stations), thick hard lateritic soil underlain by basalt (1 station) and dam galleries (4 stations).
- Data from 13-station strong-motion network (AR-240 and RFT-250 instrument types) close to Koyna Dam. Exclude data from dam top. Use data from foundation gallery because believe they can be considered as ground acceleration data. Select set of 31 significant records after scrutinizing all data.
- Correct for instrument response and filter using cut-off frequencies based on a signal-to-noise ratio > 1.
- Use a 2-stage regression method. Firstly, find C_1, C_2 and C_5 (magnitude and component dependencies) and then find updated C_1, C_3 and C_4 (distance dependence) using residuals from first stage.
- Find that equation matches the observed data quite well.

2.197 Kalkan & Gülkan (2004a)

- Ground-motion model is:

$$\begin{aligned} \ln Y_V &= C_1 + C_2(M-6) + C_3(M-6)^2 + C_4(M-6)^3 + C_5 \ln r + C_6 \Gamma_1 + C_7 \Gamma_2 \\ r &= (r_{cl}^2 + h^2)^{1/2} \end{aligned}$$

  where Y is in g, $C_1 = 0.055$, $C_2 = 0.387$, $C_3 = -0.006$, $C_4 = 0.041$, $C_5 = -0.944$, $C_6 = 0.277$, $C_7 = 0.030$, $h = 7.72\,\mathrm{km}$, $\sigma_{\mathrm{rock}} = 0.629$, $\sigma_{\mathrm{soil}} = 0.607$ and $\sigma_{\mathrm{softsoil}} = 0.575$.
- Use three site classes:

$\Gamma_1 = 0, \Gamma_2 = 0$ Rock: average $V_s = 700\,\mathrm{m/s}$, 27 records

$\Gamma_1 = 1, \Gamma_2 = 0$ Soil: average $V_s = 400\,\mathrm{m/s}$, 26 records

$\Gamma_1 = 0, \Gamma_2 = 1$ Soft soil: average $V_s = 200\,\mathrm{m/s}$, 47 records

Classify using approximate methods due to lack of available information. Note that correspondence between average V_s values for each site class and more widely accepted soil categories is tenuous.

- Focal depths from 0 to $111.0\,\mathrm{km}$. State that all earthquakes were shallow crustal events. Only 4 records come from earthquakes with reported focal depths $> 33\,\mathrm{km}$.
- Expand with data from after 1999 and update database of Gülkan & Kalkan (2002).
- Faulting mechanism distribution is: normal (12 earthquakes, 14 records), strike-slip (33 earthquakes, 81 records) and reverse (2 earthquakes, 5 records). Note that poor distribution w.r.t. mechanism does not allow its effect to be modelled.
- Use only records from earthquakes with $M_w \geq 4.5$ to emphasize motions having greatest engineering interest and to include only more reliably recorded events. Include data from one $M_w 4.2$ earthquake because of high vertical acceleration ($31\,\mathrm{mg}$) recorded.
- Data reasonably well distribution w.r.t. M and d for $d < 100\,\mathrm{km}$.
- Data mainly recorded in small and medium-sized buildings ≤ 3 storeys. Note that these buildings modify recorded motions and this is an unavoidable uncertainty of the study.
- Data from main shocks. Exclude data from aftershocks, in particular that from the 1999 Kocaeli and Düzce aftershocks because these records are from free-field stations, which do not want to commingle with non-free-field data.
- Exclude a few records for which PGA caused by main shock is $< 10\,\mathrm{mg}$. Exclude data from aftershocks from the same stations.
- Note that data used is of varying quality and could be affected by errors.
- Include cubic term for M dependence to compensate for the controversial effects of sparsity of Turkish data. Find that it gives a better fit.
- Use two-step method of Ambraseys *et al.* (1996) to find site coefficients C_6 and C_7 after exploratory analysis to find regression method that gives the best estimates and the lowest σ.
- State equations can be used for $4.5 \leq M_w \leq 7.4$ and $d_f \leq 200\,\mathrm{km}$.
- Find no significant trends in residuals w.r.t. M or d for all data and for each site category except for a few high residuals for soil and soft soil records at $d_f > 100\,\mathrm{km}$.
- Compute individual σs for each site class.
- Find that observed ground motions for the Kocaeli earthquake are well predicted.

2.198 Kalkan & Gülkan (2004b) and Kalkan & Gülkan (2005)

- Ground-motion model is:

$$\begin{aligned} \ln Y &= b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln r + b_V \ln(V_S/V_A) \\ r &= (r_{cl}^2 + h^2)^{1/2} \end{aligned}$$

where Y is in g, $b_1 = 0.393$, $b_2 = 0.576$, $b_3 = -0.107$, $b_5 = -0.899$, $b_V = -0.200$, $V_A = 1112\,\mathrm{m/s}$, $h = 6.91\,\mathrm{km}$ and $\sigma = 0.612$.

- Use three site classes:

Rock Average $V_s = 700\,\mathrm{m/s}$, 23 records

Soil Average $V_s = 400\,\mathrm{m/s}$, 41 records

Soft soil Average $V_s = 200\,\mathrm{m/s}$, 48 records

Use V_s measurements where available (10 stations, 22 records) but mainly classify using approximate methods. Note that correspondence between average V_s values for each site class and more widely accepted soil categories is tenuous.

- Focal depths from 0 to $111.0\,\mathrm{km}$. State that all earthquakes were shallow crustal events. Only 4 records come from earthquakes with reported focal depths $> 33\,\mathrm{km}$.
- Expand with data from after 1999 and update database of Gülkan & Kalkan (2002).
- Faulting mechanism distribution is: normal (12 earthquakes, 14 records), strike-slip (34 earthquakes, 82 records), reverse (2 earthquakes, 5 records), unknown (9 earthquakes, 11 records). Note that poor distribution w.r.t. mechanism does not allow its effect to be modelled.
- Use only records from earthquakes with $M_w \geq 4.0$ to include only more reliably recorded events.
- Data reasonably well distribution w.r.t. M and d for $d < 100\,\mathrm{km}$.
- Data from main shocks. Exclude data from aftershocks, in particular that from the 1999 Kocaeli and Düzce aftershocks because of high nonlinear soil behaviour observed during the mainshocks near the recording stations.
- Data mainly recorded in small and medium-sized buildings ≤ 3 storeys. Note that these buildings modify recorded motions and this is an unavoidable uncertainty of the study.
- State equations can be used for $4.0 \leq M_w \leq 7.5$ and $d_f \leq 250\,\mathrm{km}$.
- Find no significant trends in residuals w.r.t. M or d for all data and for each site category.
- Find that observed ground motions for the Kocaeli earthquake are well predicted.

2.199 Lubkowski *et al.* (2004)

- Ground-motion model is not reported. Use six functional forms.
- Use four site categories:

Very soft soil $V_{s,30} < 180\,\mathrm{m/s}$. 0 records.

Soft soil $180 \leq V_{s,30} < 360\,\mathrm{m/s}$. 1 record.

Stiff soil $360 \leq V_{s,30} < 750\,\mathrm{m/s}$. 34 records.

Rock $V_{s,30} \geq 750\,\mathrm{m/s}$. 93 records.

Site conditions are unknown for 35 records. Classify mainly using description of local site conditions owing to unavailability of V_s measurements.

- Exclude data from $M_w < 3.0$ to exclude data from earthquakes that are likely to be associated with large uncertainties in their size and location and because ground motions from smaller earthquakes are likely to be of no engineering significance.
- Exclude data from multi-storey buildings, on or in dams or on bridges.
- Most data from $M_w < 5.5$ so believe use of r_{epi} is justified.
- Records from: eastern N America (78 records), NW Europe (61 including 6 from UK) and Australia (24).
- Locations from special studies, ISC/NEIC or local network determinations.
- Note distinct lack of data from $< 10\,\mathrm{km}$ for $M_w > 5$.
- Only retain good quality strong-motion data. No instrument correction applied because of the lack of instrument characteristics for some records. Individually bandpass filter each record with a Butterworth filter with cut-offs at $25\,\mathrm{Hz}$ and cut-off frequencies chosen by examination of signal-to-noise ratio and integrated velocity and displacement traces.
- Find use of different functional forms has significant influence on predicted PGA.
- Regression on only rock data generally reduced PGA.
- Predictions using the functional forms with quadratic M-dependence were unreliable for $M_w > 5.5$ because they predict decrease PGA with increasing M since there was insufficient data from large magnitude earthquakes to constrain the predictions.
- Find different regression methods predict similar PGAs with differences of $< 5\%$ for a $M_w 5$ event at $5\,\mathrm{km}$ when all records were used but differences up to 63% when using only rock data. Prefer the one-stage maximum-likelihood method since allows for correlation between M and d in dataset and does not ignore earthquakes recorded by only a single station (25% of data).
- Find, from analysis of residuals, that equation generally underpredicts PGA of data from eastern N America and Australia but overpredicts motions from Europe and UK.
- Find no trends in residuals w.r.t. amplitude, distance, magnitude or fault mechanism.
- Believe that large σs found are due to: lack of data from close to large magnitude earthquakes, use of data from different regions with varying source and path characteristics and use of much data from small earthquakes that are probably associated with higher uncertainty w.r.t. magnitude and location since such earthquakes have not been as well studied as large earthquakes and there is a lack of data with high signal-to-noise ratio from which relocations can be made.
- Do not recommend equations for practical use due to large uncertainties.

2.200 Marin *et al.* (2004)

- Ground-motion model is:

$$\log_{10} \mathrm{PGA} = a_1 + a_2 M_L + a_3 \log_{10} R$$

  where PGA is in g, $a_1 = -3.93$, $a_2 = 0.78$, $a_3 = -1.5$ and $\sigma = 0.55$.

- All records from stiff bedrock. Shear-wave velocities estimated from geology gives: $1200–2000\,\mathrm{m/s}$ for carbonated formations and $> 2500\,\mathrm{m/s}$ for eruptive formations (majority of data).
- Derive equation since find previous equations are not consistent with recent data recorded in France and because of differences between M_L of LDG and other M_L scales.
- Use data from the Alps, the Pyrenees and Armorican Massif recorded by LDG network of vertical seismometers between 1995 and 1996. Convert vertical PGAs to horizontal PGAs using empirical relation of Smit (1998).
- Focal depths between 2 and $12\,\mathrm{km}$.
- 11 records from $3 \le d_e \le 50\,\mathrm{km}$, 34 from $50 < d_e \le 200\,\mathrm{km}$ and 18 from $d_e > 200\,\mathrm{km}$ (all from two largest earthquakes with $M_L 5.3$ and $M_L 5.6$).
- Plot predictions and data from rock sites of all French earthquakes with $M_L \ge 4$ recorded by RAP network (largest three earthquakes have $M_L 5.5$, $M_L 5.7$ and $M_L 5.9$) and find good agreement. State that this agreement shows that equation can be extrapolated to strongest earthquakes considered for France.
- Note that it will be possible to establish a more robust equation using increasing number of data from RAP, especially from near field and large magnitudes.

2.201 Midorikawa & Ohtake (2004)

- Ground-motion models are:

$$\begin{aligned}\log A &= b - \log(X + c) - kX \quad \text{for } D \le 30\,\mathrm{km}\\ \log A &= b + 0.6\log(1.7D + c) - 1.6\log(X + c) - kX \quad \text{for } D > 30\,\mathrm{km}\\ \text{where} \quad b &= aM_w + hD + d_iS_i + e\end{aligned}$$

  where A is in gal, $a = 0.59$, $c = 0.0060 \times 10^{0.5M_w}$ (adopted from Si & Midorikawa (2000)), $d_1 = 0.00$ (for crustal earthquakes), $d_2 = 0.08$ (for inter-plate earthquakes), $d_3 = 0.30$ (for intra-plate earthquakes), $e = 0.02$, $h = 0.0023$, $k = 0.003$ [adopted from Si & Midorikawa (2000)], $\sigma_{\mathrm{intra-event}} = 0.27$ and $\sigma_{\mathrm{inter-event}} = 0.16$.

- Use two site categories [definitions of Joyner & Boore (1981)]:

  Rock

  Soil

  Use $V_{s,30}$ where available. Multiply PGA values from rock sites by 1.4 to normalise them w.r.t. PGA at soil sites.

- All records from the free-field or small buildings where soil-structure interaction is negligible.
- Data from different types of instruments hence instrument correct and bandpass filter.
- Classify earthquakes into these three types:

$S_1 = 1$, $S_2 = S_3 = 0$ Crustal. 12 earthquakes, 1255 records. Focal depths, D, between 3 and $30\,\mathrm{km}$.

$S_2 = 1, S_1 = S_3 = 0$ Inter-plate. 10 earthquakes, 640 records. $6 \leq D \leq 49\,\mathrm{km}$.

$S_3 = 1, S_1 = S_2 = 0$ Intra-plate, 11 earthquakes, 1440 records. $30 \leq D \leq 120\,\mathrm{km}$.

- Most data from $M_w < 7$. No data between 6.9 and 7.6.
- Use separate functional forms for $D \leq 30\,\mathrm{km}$ and $D > 30\,\mathrm{km}$ because of significantly faster decay for deeper earthquakes.
- Plot histograms of residuals and conclude that they are lognormally distributed.
- Compute σ for 4 M ranges: 5.5–5.9, 6.0–6.5, 6.6–6.9 and 7.6–8.3. Find slight decrease in σ w.r.t. M.
- Compute σ for ranges of $20\,\mathrm{km}$. Find significantly smaller σs for distances $< 50\,\mathrm{km}$ and almost constant σs for longer distances.
- Compute σ for ranges of PGA of roughly $50\,\mathrm{km}$. Find much larger σs for small PGA than for large PGA.
- Believe that main cause of M-dependent σ is that stress-drop is M-dependent and that radiation pattern and directivity are not likely to be significant causes.
- Believe that distance-dependent σ is likely to be due to randomness of propagation path (velocity and Q-structure).
- Believe site effects do not contribute greatly to the variance.
- Plot PGA versus distance and observe a saturation at several hundred $\mathrm{cm/s^2}$, which suggest may be due to nonlinear soil behaviour.
- Plot σ w.r.t. PGA for three site categories: $100 \leq V_{s,30} \leq 300\,\mathrm{m/s}$, $300 \leq V_{s,30} \leq 600\,\mathrm{m/s}$ and $600 \leq V_{s,30} \leq 2600\,\mathrm{m/s}$. Find σ lower for soft soils than for stiff soils, which believe may demonstrate that nonlinear soil response is a cause of PGA-dependent σ.
- Note that because inter-event σ is significantly smaller than intra-event σ, source effects are unlikely to be the main cause for observed σ dependencies.

2.202 Özbey *et al.* (2004)

- Ground-motion model is:

$$\log(Y) = a + b(M-6) + c(M-6)^2 + d\log\sqrt{R^2+h^2} + eG_1 + fG_2$$

  where Y is in $\mathrm{cm/s^2}$, $a = 3.287$, $b = 0.503$, $c = -0.079$, $d = -1.1177$, $e = 0.141$, $f = 0.331$, $h = 14.82\,\mathrm{km}$ and $\sigma = 0.260$.

- Use three site classes:

$G_1 = 0, G_2 = 0$ A: shear-wave velocity $> 750\,\mathrm{m/s}$, 4 records, and B: shear-wave velocity 360–$750\,\mathrm{m/s}$, 20 records.

$G_1 = 1, G_2 = 0$ C: shear-wave velocity 180–$360\,\mathrm{m/s}$, 35 records.

$G_1 = 0, G_2 = 1$ D: shear-wave velocity $< 180\,\mathrm{m/s}$, 136 records.

Originally A and B were separate but combine due to lack of data for site class A.

- Focal depths between 5.4 and $25.0\,\mathrm{km}$.
- Use M_w for $M > 6$ to avoid saturation effects.
- Assume $M_L = M_w$ for $M \leq 6$.
- Select records from earthquakes with $M \geq 5.0$.
- Most (15 earthquakes, 146 records) data from earthquakes with $M \leq 5.8$.
- Only use data from the Earthquake Research Department of General Directorate of Disaster Affairs from $d_f \leq 100\,\mathrm{km}$.
- Exclude record from Bolu because of possible instrument error.
- Use mixed effects model to account for both inter-event and intra-event variability.
- Find that the mixed effects model yields σs lower than fixed effects model.
- Compare predictions with observed data from the Kocaeli and Düzce earthquakes and find reasonable fit.
- Plot coefficients and σs against frequency and find dependence on frequency.
- Plot inter-event and intra-event residuals against distance and magnitude and find not systematic trends.
- Find intra-event residuals are significantly larger than inter-event residuals. Suggest that this is because any individual event's recordings used to develop model follow similar trends with associated parameters.
- Recommend that equations are only used for ground-motion estimation in NW Turkey.

2.203 Pankow & Pechmann (2004) and Pankow & Pechmann (2006)

- Ground-motion model is:

$$\begin{aligned}\log_{10}(Z) &= b_1 + b_2(M-6) + b_3(M-6)^2 + b_5\log_{10}D + b_6\Gamma \\ D &= (r_{jb}^2 + h^2)^{1/2}\end{aligned}$$

  where Z is in g, $b_1 = 0.237$, $b_2 = 0.229$, $b_3 = 0$, $b_5 = -1.052$, $b_6 = 0.174$, $h = 7.27\,\mathrm{km}$ and $\sigma_{\log Z} = 0.203$ (see Spudich & Boore (2005) for correct value of σ_3 for use in calculating σ for randomly-orientated component).

- Use two site classes:

$\Gamma = 0$ Rock: sites with soil depths of $< 5\,\mathrm{m}$.

$\Gamma = 1$ Soil

- Use data of Spudich *et al.* (1999).
- Correct equations of Spudich *et al.* (1999) for 20% overprediction of motions for rock sites, which was due either to underestimation of shear-wave velocities for rock sites for extensional regimes (believed to be more likely) or an overestimation of shear-wave velocities at soil sites. Correction based on adjusting b_1 and b_6 to eliminate bias in rock estimates but leave soil estimates unchanged.

- Verify that adjustment reduces bias in rock estimates.
- Do not change $\sigma_{\log Z}$ because changes to b_1 and b_6 have a negligible influence on $\sigma_{\log Z}$ w.r.t. errors in determining $\sigma_{\log Z}$.

2.204 Sunuwar *et al.* (2004)

- Ground-motion model is:

$$\log Y(T) = b_1(T) + b_2(T)M_{\mathrm{J}} - b_3(T)D - b_4(T)\log(R)$$

  where $Y(T)$ is in $\mathrm{cm/s^2}$, $b_1(0) = 1.1064$, $b_2(0) = 0.2830$, $b_3(0) = 0.0076$, $b_4(0) = 0.6322$ and $\sigma = 0.303$ for horizontal PGA and $b_1(0) = 0.7134$, $b_2(0) = 0.3091$, $b_3(0) = 0.0069$, $b_4(0) = 0.7421$ and $\sigma = 0.301$ for vertical PGA.

- Records from 225 stations of K-Net network with $39.29 \leq V_{s,30} \leq 760.25\,\mathrm{m/s}$ (mean $V_{s,30} = 330.80\,\mathrm{m/s}$.
- Select earthquakes that occurred within the region of the boundary of the Okhotsk-Amur plates (NE Japan bordering Sea of Japan) defined by its horizontal location and vertically, to exclude earthquakes occurring in other plates or along other boundaries.
- Focal depths, D, between 8 and $43\,\mathrm{km}$ with mean depth of $20.8\,\mathrm{km}$.
- Mean value of M is 4.72.
- Mean r_{epi} is $84.67\,\mathrm{km}$.
- State that exclude records with PGA $< 5\,\mathrm{cm/s^2}$ (although ranges of PGAs given include records with PGA $< 5\,\mathrm{cm/s^2}$).
- Horizontal PGA range: 4.15–$411.56\,\mathrm{cm/s^2}$. Vertical PGA range: 0.50–$163.11\,\mathrm{cm/s^2}$.
- Originally use this form: $\log Y(T) = b_1(T) + b_2(T)M - b_3(T)D - \log(R) + b_5(T)R$ but find $b_5(T) > 0$. Regress using the 379 records from sites with $V_{s,30} > 300\,\mathrm{m/s}$ and still find $b_5(T) > 0$ but report results for investigating site effects.
- Plot residuals w.r.t. r_{hypo} and find mean of residuals is zero but find some high residuals.
- Note that need to refine model to consider site effects.

2.205 Skarlatoudis *et al.* (2004)

- Ground-motion model is:

$$\log Y = c_0 + c_1 M + c_2 \log(R^2 + h^2)^{1/2}$$

  where Y is in $\mathrm{cm/s^2}$, $c_0 = 1.03$, $c_1 = 0.32$, $c_2 = -1.11$, $h = 7\,\mathrm{km}$ and $\sigma = 0.34$.

- Classify stations into four NEHRP categories: A, B, C and D (through a site coefficient, c_4) but find practically no effect so neglect.
- Aim to investigate scaling of ground motions for small magnitude earthquakes.

- Most earthquakes have normal mechanisms from aftershock sequences.
- Records from permanent and temporary stations of ITSAK network. Many from Euro-SeisTest array.
- Records from ETNA, K2, SSA-1 and SSA-2 plus very few SMA-1 instruments.
- Filter records based on a consideration of signal-to-noise ratio. For digital records use these roll-off and cut-off frequencies based on magnitude (after studying frequency content of records and applying different bandpass filters): for $2 \leq M_w < 3$ $f_r = 0.95\,\mathrm{Hz}$ and $f_c = 1.0\,\mathrm{Hz}$, for $3 \leq M_w < 4$ $f_r = 0.65\,\mathrm{Hz}$ and $f_c = 0.7\,\mathrm{Hz}$ and for $4 \leq M_w < 5$ $f_r = 0.35$ and $f_c = 0.4\,\mathrm{Hz}$. Find that this method adequately removes the noise from the accelerograms used.
- Use source parameters computed from high-quality data from local networks. Note that because focal parameters are from different institutes who use different location techniques may mean data set is inhomogeneous.
- Note that errors in phase picking in routine location procedures may lead to less accurate locations (especially focal depths) for small earthquakes as opposed to large earthquakes due to indistinct first arrivals.
- To minimize effects of focal parameter uncertainties, fix h as $7\,\mathrm{km}$, which corresponds to average focal depth in Greece and also within dataset used.
- Exclude data from $d_e > 40\,\mathrm{km}$ because only a few (3% of total) records exist for these distances and also to exclude far-field records that are not of interest.
- Most records from $d_e < 20\,\mathrm{km}$ and $2.5 \leq M_w \leq 4.5$.
- Also derive equations using this functional form: $\log Y = c_0 + c_1 M + c_2 \log(R + c_3)$ where c_3 was constrained to $6\,\mathrm{km}$ from an earlier study due to problems in deriving reliable values of c_2 and c_3 directly by regression.
- Use singular value decomposition for regression following Skarlatoudis *et al.* (2003).
- Combined dataset with dataset of Skarlatoudis *et al.* (2003) and regress. Find significant number of data outside the $\pm 1\sigma$ curves. Also plot average residual at each M w.r.t. M and find systematically underestimation of PGA for $M_w \geq 5$. Conclude that this shows the insufficiency of a common relation to describe both datasets.
- Find no trends in the residuals w.r.t. magnitude or distance.
- Find that the predominant frequencies of PGAs are $< 15\,\mathrm{Hz}$ so believe results not affected by low-pass filtering at 25–$27\,\mathrm{Hz}$.

2.206 Ulusay *et al.* (2004)

- Ground-motion model is:

$$\mathrm{PGA} = a_1 \mathrm{e}^{a_2(a_3 M_w - R_e + a_4 S_A + a_5 S_B)}$$

where PGA is in gal, $a_1 = 2.18$, $a_2 = 0.0218$, $a_3 = 33.3$, $a_4 = 7.8427$, $a_5 = 18.9282$ and $\sigma = 86.4$.

- Use three site categories:

$S_A = 0$, $S_B = 0$ Rock, 55 records.

$S_A = 1$, $S_B = 0$ Soil, 94 records.

$S_A = 0$, $S_B = 1$ Soft soil, 72 records.

  Classify by adopting those given by other authors, selecting the class reported by more than one source.

- Most data from instruments in small buildings.
- Use records with PGA $> 20\,\mathrm{gal}$ to avoid bias due to triggering.
- PGAs of records between 20 and $806\,\mathrm{gal}$.
- Use records from earthquakes with $M_w \geq 4$ because smaller earthquakes are generally not of engineering significance.
- Derive linear conversion formulae (correlation coefficients > 0.9) to transform M_s (39), m_b (18), M_d (10) and M_L (6) to M_w (73 events in total).
- Note that rupture surfaces have not been accurately defined for most events therefore use r_{epi}.
- Note that accurate focal depths are often difficult to obtain and different data sources provide different estimates therefore do not use r_{hypo}.
- Use records from $\geq 5\,\mathrm{km}$ because of assumed average error in epicentral locations.
- Use records from $\leq 100\,\mathrm{km}$ because this is the distance range where engineering significant ground motions occur.
- Most data from $M_w \leq 6$ and $d_e \leq 50\,\mathrm{km}$.
- Do not consider faulting mechanism because focal mechanism solutions for most earthquakes not available.
- Plot observed versus predicted PGA and find that a few points fall above and below the lines with slopes $1 : 0.5$ and $1 : 2$ but most are between these lines.
- Note that to improve precision of equation site characterisation based on V_s measurements should be included. Also note that directivity, fault type and hanging wall effects should be considered when sufficient data is available.

2.207 Ambraseys *et al.* (2005a)

- Ground-motion model is:

$$\log y = a_1 + a_2 M_w + (a_3 + a_4 M_w) \log \sqrt{d^2 + a_5^2} + a_6 S_S + a_7 S_A + a_8 F_N + a_9 F_T + a_{10} F_O$$

  where y is in $\mathrm{m/s^2}$, $a_1 = 2.522$, $a_2 = -0.142$, $a_3 = -3.184$, $a_4 = 0.314$, $a_5 = 7.6$, $a_6 = 0.137$, $a_7 = 0.050$, $a_8 = -0.084$, $a_9 = 0.062$, $a_{10} = -0.044$, $\sigma_1 = 0.665 - 0.065 M_w$ (intra-event) and $\sigma_2 = 0.222 - 0.022 M_w$ (inter-event).

- Use three site categories:

$S_S = 1$, $S_A = 0$ Soft soil (S), $180 < V_{s,30} \leq 360\,\mathrm{m/s}$. 143 records.

$S_S = 0$, $S_A = 1$ Stiff soil (A), $360 < V_{s,30} \leq 750\,\mathrm{m/s}$. 238 records.

$S_S = 0$, $S_A = 0$ Rock (R), $V_{s,30} > 750\,\mathrm{m/s}$. 203 records.

  Originally include a fourth category, very soft soil ($V_{s,30} \leq 180\,\mathrm{m/s}$), but only included 11 records so combined with soft soil records. Note that measured $V_{s,30}$ only exist for 89 of 338 stations contributing 161 records so use descriptions of local site conditions to classify stations. Exclude records from stations with unknown site conditions because could not be handled by chosen regression method.

- Use only data from Europe and Middle East because believe their databank is reasonably complete for moderate and large earthquakes that occurred in region. Also these data have been carefully reviewed in previous studies. Finally based on a previous study believe motions in California could be significantly higher than those in Europe. Note that including these data would increase the quantity of high-quality near-source data available.

- Combine data from all seismically active parts of Europe and the Middle East into a common dataset because a previous study shows little evidence for regional differences between ground motions in different regions of Europe.

- Only use earthquakes with a M_0 estimate for which to calculate M_w. Do not convert magnitudes from other scales because this increases the uncertainty in the magnitude estimates. Exclude records from earthquakes with $M_w < 5$ in order to have a good distribution of records at all magnitudes. Note that this also excludes records from small earthquakes that are unlikely to be of engineering significance.

- Use r_{jb} because does not require a depth estimate, which can be associated with a large error.

- Exclude records from $> 100\,\mathrm{km}$ because: excludes records likely to be of low engineering significance, reduces possible bias due to non-triggering instruments, reduces effect of differences in anelastic decay in different regions and it gives a reasonably uniform distribution w.r.t. magnitude and distance, which reduces likelihood of problems in regression analysis.

- Use only earthquakes with published focal mechanism in terms of trends and plunges of T, B and P axes because estimating faulting type based on regional tectonics or to be the same as the associated mainshock can lead to incorrect classification. Classify earthquakes using method of Frohlich & Apperson (1992):

Thrust Plunge of T axis $> 50°$. 26 earthquakes, 91 records, $F_T = 1$, $F_N = 0$, $F_O = 0$.

Normal Plunge of P axis $> 60°$. 38 earthquakes, 191 records, $F_T = 0$, $F_N = 1$, $F_O = 0$.

Strike-slip Plunge of B axis $> 60°$. 37 earthquakes, 160 records, $F_T = 0$, $F_N = 0$, $F_O = 0$.

Odd All other earthquakes. 34 earthquakes, 153 records, $F_T = 0$, $F_N = 0$, $F_O = 1$.

  Use this method because does not require knowledge of which plane is the main plane and which the auxiliary.

- Do not exclude records from ground floors or basements of large buildings because of limited data.
- Exclude records from instruments that triggered late and those that were poorly digitised.
- Instrument correct records and then apply a low-pass filter with roll-off and cut-off frequencies of 23 and $25\,\mathrm{Hz}$ for records from analogue instruments and 50 and $100\,\mathrm{Hz}$ for records from digital instruments. Select cut-off frequencies for high-pass bidirectional Butterworth filtering based on estimated signal-to-noise ratio and also by examining displacement trace. For records from digital instruments use pre-event portion of records as noise estimate. For those records from analogue instruments with an associated digitised fixed trace these were used to estimate the cut-offs. For records from analogue instruments without a fixed trace examine Fourier amplitude spectrum and choose the cut-offs based on where the spectral amplitudes do not tend to zero at low frequencies. Note that there is still some subjective in the process. Next choose a common cut-off frequency for all three components. Use a few records from former Yugoslavia that were only available in corrected form.
- Only use records with three usable components in order that ground-motion estimates are unbiased and that mutually consistent horizontal and vertical equations could be derived.
- Note lack of data from large ($M_w > 6.5$) earthquakes particularly from normal and strike-slip earthquakes.
- Data from: Italy (174 records), Turkey (128), Greece (112), Iceland (69), Albania (1), Algeria (3), Armenia (7), Bosnia & Herzegovina (4), Croatia (1), Cyprus (4), Georgia (14), Iran (17), Israel (5), Macedonia (1), Portugal (4), Serbia & Montenegro (24), Slovenia (15), Spain (6), Syria (5) and Uzbekistan (1).
- Note that much strong-motion data could not be used due to lack of local site information.
- Select one-stage maximum-likelihood regression method because accounts for correlation between ground motion from same earthquake whereas ordinary one-stage method does not. Note that because there is little correlation between M_w and distance in the data used (correlation coefficient of 0.23) ordinary one-stage and one-stage maximum-likelihood methods give similar coefficients. Do not use two-stage maximum-likelihood method because underestimates σ for sets with many singly-recorded earthquakes (35 earthquakes were only recorded by one station). Do not use method that accounts for correlation between records from same site because records are used from too many different stations and consequently method is unlikely to lead to an accurate estimate of the site-to-site variability (196 stations contribute a single record). Do not use methods that account for uncertainty in magnitude determination because assume all magnitude estimates are associated with the same uncertainty since all M_w are derived from published M_0 values.
- Apply pure error analysis of Douglas & Smit (2001). Divide dataspace into $0.2M_w$ units by $2\,\mathrm{km}$ intervals and compute mean and unbiased standard deviation of untransformed ground motion in each bin. Fit a linear equation to graphs of coefficient of variation against ground motion and test if slope of line is significantly different (at 5% significance level) than zero. If it is not then the logarithmic transformation is justified. Find that slope of line is not significantly different than zero so adopt logarithmic transformation of ground motion.

- Use pure error analysis to compute mean and unbiased standard deviation of logarithmically transformed ground motion in each $0.2M_w \times 2\,\mathrm{km}$ bin. Plot the standard deviations against M_w and fit linear equation. Test significance (5% level) of slope. Find that it is significantly different than zero and hence magnitude-independent standard deviation is not justified. Use the reciprocals of fitted linear equations as weighting functions for regression analysis.
- Using the standard deviations computed by pure error analysis for each bin estimate lowest possible σ for derived equations.
- Investigate possible magnitude-dependence of decay rate of ground motions using ten best-recorded earthquakes (total number of records between 13 and 26). Fit PGAs for each earthquake with equation of form: $\log y = a_1 + a_2 \log \sqrt{d^2 + a_3^2}$. Plot decay rates ($a_2$) against M_w and fit a linear equation. Find that the fitted line has a significant slope and hence conclude that data supports a magnitude-dependent decay rate. Assume a linear dependence between decay rate and M_w due to limited data.
- Try including a quadratic magnitude term in order to model possible differences in scaling of ground motions for earthquakes that rupture entire seismogenic zone. Find that term is not significant at 5% level so drop.
- Could not simultaneously find negative geometric and anelastic decay coefficients so assume decay attributable to anelastic decay is incorporated into geometric decay coefficient.
- Test significance of all coefficients at 5% level. Retain coefficients even if not significant.
- Note that there is not enough data to model possible distance dependence in effect of faulting mechanism or nonlinear soil effects.
- Compute median amplification factor (anti-logarithm of mean residual) for the 16 stations that have recorded more than five earthquakes. Find that some stations show large amplifications or large deamplifications due to strong site effects.
- Compute median amplification factor for the ten best recorded earthquakes. Find that most earthquakes do not show significant overall differences but that a few earthquakes do display consistently lower or higher ground motions.
- Plot residual plots w.r.t. weighted M_w and weighted distance and find no obvious dependence of scatter on magnitude or distance.
- Plot histograms of binned residuals.
- Compare predicted and observed PGAs from the 2004 Parkfield earthquake and find a close match. Note that this may mean that the exclusion of data from California based on possible differences in ground motions was not justified.

2.208 Ambraseys *et al.* (2005b)

- Ground-motion model is:

$$\log y = a_1 + a_2 M_w + (a_3 + a_4 M_w) \log \sqrt{d^2 + a_5^2} + a_6 S_S + a_7 S_A + a_8 F_N + a_9 F_T + a_{10} F_O$$

where y is in $\mathrm{m/s^2}$, $a_1 = 0.835$, $a_2 = 0.083$, $a_3 = -2.489$, $a_4 = 0.206$, $a_5 = 5.6$, $a_6 = 0.078$, $a_7 = 0.046$, $a_8 = -0.126$, $a_9 = 0.005$, $a_{10} = -0.082$, $\sigma_1 = 0.262$ (intra-event) and $\sigma_2 = 0.100$ (inter-event).

- Based on Ambraseys *et al.* (2005a). See Section 2.207.

2.209 Bragato (2005)

- Ground-motion model is:

$$\log_{10}(\mathrm{PGA}) = c_1 + c_2 M_s + c_3 r$$

where PGA is in $\mathrm{m/s^2}$, $c_1 = -2.09$, $c_2 = 0.47$, $c_3 = -0.039$ and $\sigma = 0.3$ (note that the method given in the article must be followed in order to predict the correct accelerations using this equation).

- Uses data (186 records) of Ambraseys & Douglas (2000, 2003) for $M_s \geq 5.8$. Add 57 records from ISESD (Ambraseys *et al.* , 2004) for $5.0 \leq M_s \leq 5.7$.

- Investigates whether 'magnitude-dependent attenuation', i.e. PGA saturation in response to increasing magnitude, can be explained by PGA approaching an upper physical limit through an accumulation of data points under an upper limit.

- Proposes model with: a magnitude-independent attenuation model and a physical mechanism that prevents PGA from exceeding a given threshold. Considers a fixed threshold and a threshold with random characteristics.

- Develops the mathematical models and regression techniques for the truncated and the randomly clipped normal distribution.

- Reduces number of parameters by not considering site conditions or rupture mechanism. Believes following results of Ambraseys & Douglas (2000, 2003) that neglecting site effects is justified in the near-field because they have little effect. Believes that the distribution of data w.r.t. mechanism is too poor to consider mechanism.

- Performs a standard one-stage, unweighted regression with adopted functional form and also with form: $\log_{10}(\mathrm{PGA}) = c_1 + c_2 M + c_3 r + c_4 M r + c_5 M^2 + c_6 r^2$ and finds magnitude saturation and also decreasing standard deviation with magnitude.

- Performs regression with the truncation model for a fixed threshold with adopted functional form. Finds almost identical result to that from standard one-stage, unweighted regression.

- Performs regression with the random clipping model. Finds that it predicts magnitude-dependent attenuation and decreasing standard deviation for increasing magnitude.

- Investigates the effect of the removal of high-amplitude ($\mathrm{PGA} = 17.45\,\mathrm{m/s^2}$) record from Tarzana of the 1994 Northridge earthquake. Finds that it has little effect.

2.210 Bragato & Slejko (2005)

- Ground-motion model is:

$$\begin{aligned}\log_{10}(Y) &= a + (b + cM)M + (d + eM^3)\log_{10}(r)\\ r &= \sqrt{d^2 + h^2}\end{aligned}$$

  where Y is in g, $a = -3.27$, $b = 1.95$, $c = -0.202$, $d = -3.11$, $e = 0.00751$, $h = 8.9\,\mathrm{km}$ and $\sigma = 0.399$ for horizontal PGA and r_{epi}, $a = -3.37$, $b = 1.93$, $c = -0.203$, $d = -3.02$, $e = 0.00744$, $h = 7.3\,\mathrm{km}$ and $\sigma = 0.358$ for horizontal PGA and r_{jb}, $a = -2.96$, $b = 1.79$, $c = -0.184$, $d = -3.26$, $e = 0.00708$, $h = 11.3\,\mathrm{km}$ and $\sigma = 0.354$ for vertical PGA and r_{epi} and $a = -3.18$, $b = 1.80$, $c = -0.188$, $d = -3.13$, $e = 0.00706$, $h = 9.1\,\mathrm{km}$ and $\sigma = 0.313$ for vertical PGA and r_{jb}.

- Believe relation valid for rather rigid soil.

- Use data from the Seismometric Network of Friuli-Venezia Giulia (SENF) (converted to acceleration), the Friuli Accelerometric Network (RAF), data from the 1976 Friuli sequence and data from temporary seismometric (converted to acceleration) and accelerometric stations of Uprava RS za Geofiziko (URSG) of the 1998 Bovec sequence.

- Data from 1976 Friuli sequence is taken from ISESD. Records have been bandpass filtered with cut-offs of 0.25 and $25\,\mathrm{Hz}$. No instrument correction has been applied. Data from other networks has been instrument corrected and high-pass filtered at $0.4\,\mathrm{Hz}$.

- Hypocentral locations and M_L values adopted from local bulletins and studies.

- Use running vectorial composition of horizontal time series because horizontal vector is the actual motion that intersects seismic hazard. Find that on average running vectorial composition is 8% larger than the larger horizontal peak and 27% larger than the geometric mean. Find that using other methods to combine horizontal components simply changes a by about 0.1 downwards and does not change the other coefficients.

- Use data from 19 earthquakes with $M_L \geq 4.5$ (161 vertical records, 130 horizontal records).

- Note that distribution w.r.t. magnitude of earthquakes used roughly follows log-linear Gutenberg-Richter distribution up to about $M_L \geq 4.5$.

- Few records available for $d < 10\,\mathrm{km}$ and $M_L > 3$.

- Focal depths between 1.0 and $21.6\,\mathrm{km}$. Average depth is $11.4 \pm 3.6\,\mathrm{km}$.

- Apply multi-linear multi-threshold truncated regression analysis (TRA) of Bragato (2004) to handle the effect of nontriggering stations using the simplification that for SENF and URSG data the random truncation level can be approximated by the lowest value available in the data set for that station. For data from the 1976 Friuli sequence use a unique truncation level equal to the minimum ground motion for that entire network in the dataset. Use same technique for RAF data.

- Develop separate equations for r_{epi} and r_{jb} (available for 48 records in total including all from $M_L > 5.8$). Note that physically r_{jb} is a better choice but that r_{epi} is more similar to geometric distance used for seismic hazard assessment.

- Use M_L because available for regional earthquakes eastern Alps since 1972.
- Conduct preliminary tests and find that weak-motion data shows higher attenuation than strong-motion data. Investigate horizontal PGA using entire data set and data for 0.5-wide magnitude classes. Find that attenuation is dependent on magnitude and it is not useful to include a coefficient to model anelastic attenuation.
- Since data is not uniformly distributed with magnitude, inversely weight data by number of records within intervals of 0.1 magnitude units wide.
- Because correlation between magnitude and distance is very low (0.03 and 0.02 for vertical and horizontal components, respectively) apply one-stage method.
- Note that large differences between results for r_{epi} and r_{jb} are due to magnitude-dependent weighting scheme used.
- Plot predicted and observed ground motions binned into 0.3 magnitude intervals and find close match.
- Plot residuals w.r.t. focal depth, r_{jb} and M_L. Find that it appears equation over-estimates horizontal PGA for $d_f > 80\,\mathrm{km}$, $M_L < 3$ and focal depths $> 15\,\mathrm{km}$ but note that this is due to the truncation of low amplitude data. Check apparent trend using TRA and find no significant trend.
- Note that difficult to investigate importance of focal depth on attenuation due to unreliability of depths particularly for small earthquakes. Find that focal depths seem to be correlated to magnitude but believe that this is an artifact due to poor location of small earthquakes. Try regression using r_{hypo} and find larger σ hence conclude that depth estimates are not accurate enough to investigate effect of depth on ground motions.
- Investigate methods for incorporation of site effect information using their ability to reduce σ as a criteria.
- Note that largest possible reduction is obtained using individual average station residuals for each site but that this is not practical because this method cannot be used to predict ground motions at arbitrary site and that it requires sufficient number of observations for each station. Using just those stations that recorded at least five earthquakes obtain estimate of lowest possible σ by adopting this method.
- Try using a classification of stations into three site categories: rock (16 stations, 1020 records), stiff soil (9 stations, 117 records) and soft soil (4 stations, 27 records) and find no reduction in σ, which believe is due to the uneven distribution w.r.t. site class. Find that the strong site effects at Tolmezzo has a significant effect on the obtained site coefficients.
- Use Nakamura (H/V) ratios from ambient noise for a selection of stations by including a term $g(S) = c_{\mathrm{HV}} N(S)$, where $N(S)$ is the Nakamura ratio at the period of interest (0.125–$1\,\mathrm{s}$ for PGA), in the equation. Find large reductions in σ and high correlations between Nakamura ratios and station residuals.
- Use receiver functions from earthquake recordings in a similar way to Nakamura ratios. Find that it is reduces σ more than site classification technique but less than using the Nakamura ratios, which note could be because the geometry of the source affects the computed receiver functions so that they are not representative of the average site effects.

- Believe equation is more appropriate than previous equations for $M_L < 5.8$ and equivalent to the others up to $M_L 6.3$. Discourage extrapolation for $M_L > 6.3$ because it overestimates PGA in the far-field from about $M_L 6.5$.

2.211 Frisenda *et al.* (2005)

- Ground-motion model is:

$$\log(Y) = a + bM + cM^2 + d\log(R) + eS$$

  where Y is in g, $a = -3.19 \pm 0.02$, $b = 0.87 \pm 0.01$, $c = -0.042 \pm 0.002$, $d = -1.92 \pm 0.01$, $e = 0.249 \pm 0.005$ and $\sigma = 0.316$.

- Use two site classes, because lack local geological information (e.g. average V_s):

$S = 0$ Rock, eight stations, 3790 records.

$S = 1$ Soil, seven stations, 3109 records.

  Classify station using geological reports, M_L station corrections and H/V spectral ratios computed over a $30\,\mathrm{s}$ wide time window of S waves for entire waveform data set.

- Data from Regional Seismic Network of Northwestern Italy and Regional Seismic Network of Lunigiana-Garfagnana (ten Lennartz LE3D-5s and five Guralp CMG-40 sensors with Lennartz Mars88/MC recording systems). Sampling rate either 62.5 or $125\,\mathrm{samples/s}$. Records from broadband and enlarged band seismometers converted to acceleration by: correcting for instrument response, bandpass filtering between 1 and $20\,\mathrm{Hz}$ and then differentiating. Accuracy of conversion verified by comparing observed and derived PGA values at one station (STV2), which was equipped with both a Kinemetrics K2 accelerometer and a Guralp CMG-40 broadband sensor.

- Find strong attenuation for short distances ($< 50\,\mathrm{km}$) and small magnitudes ($M_L < 3.0$).

- M_L calculated using a calibration formula derived for northwestern Italy using a similar dataset.

- Compute signal-to-noise (S/N) ratio for the S phase using windows of $3\,\mathrm{s}$ wide and find that data is good quality (85% of windows have S/N ratio greater than $10\,\mathrm{dB}$. Only use records with S/N ratio $> 20\,\mathrm{dB}$.

- Most earthquakes are from SW Alps and NW Apennines.

- Most records from earthquakes with $1 \leq M_L \leq 3$, small number from larger earthquakes particularly those with $M_L > 4$. $M_L < 1$: 1285 records, $1 \leq M_L < 2$: 2902 records, $2 \leq M_L < 3$: 1737 records, $3 \leq M_L < 4$: 693 records and $M_L \geq 4$: 282 records.

- Data shows strong magnitude-distance correlation, e.g. records from earthquakes with $M_L < 1$ are from $0 \leq R \leq 100\,\mathrm{km}$ and those from earthquakes with $M_L > 4$ are mainly from $R > 50\,\mathrm{km}$. Distribution is uniform for $2 \leq M_L \leq 4$ and $0 \leq R \leq 200\,\mathrm{km}$.

- Originally include an anelastic decay term ($d_1 R$) in addition but the value of d_1 was positive and not statistically significantly different than zero so it was removed.

- Regression in two-steps: firstly without site effect coefficient (e) and then with e added.

- Compare data to estimated decay within one magnitude unit intervals and find predictions are good up to $M_L = 4.0$.
- Find no systematic trends in the residuals.

2.212 García *et al.* (2005)

- Ground-motion model is:

$$\begin{aligned}\log Y &= c_1 + c_2 M_w + c_3 R - c_4 \log R + c_5 H \\ R &= \sqrt{R_{\text{cld}}^2 + \Delta^2} \\ \Delta &= 0.00750 \times 10^{0.507 M_w}\end{aligned}$$

  where Y is in cm/s^2, for horizontal PGA: $c_1 = -0.2$, $c_2 = 0.59$, $c_3 = -0.0039$, $c_4 = 1$, $c_5 = 0.008$, $\sigma_r = 0.27$, $\sigma_e = 0.10$ and for vertical PGA: $c_1 = -0.4$, $c_2 = 0.60$, $c_3 = -0.0036$, $c_4 = 1$, $c_5 = 0.006$, $\sigma_r = 0.25$ and $\sigma_e = 0.11$ where σ_r is the intra-event standard deviation and σ_e is the inter-event standard deviation.
- All data from 51 hard (NEHRP B) sites.
- All stations in the Valley of Mexico omitted.
- All data from free-field stations: small shelters, isolated from any building, dam abutment, bridge, or structure with more than one storey.
- Focal depths: $35 \leq H \leq 138\,\text{km}$, most records (13 earthquakes, 249 records) from $35 \leq H \leq 75\,\text{km}$.
- Exclude data from $M_w < 5.0$ and $R > 400\,\text{km}$.
- Exclude data from deep earthquakes where wave paths cross the mantle edge.
- All data from normal-faulting earthquakes.
- Use about 27 records from velocity records from broadband seismograph network that were differentiated to acceleration.
- Adopt Δ from Atkinson & Boore (2003).
- Investigate a number of functional forms. Inclusion of Δ substantially improves fit, leading to a decrease in random variability at close distances, and an increase in c_2 and c_3 coefficients. Find worse correlation when add a quadratic magnitude term. A magnitude-dependent c_4 leads to higher σs. Find unrealistically high ground motions at close distances using the form of c_4 used by Atkinson & Boore (2003).
- If exclude three deep earthquakes then little dependence on H.
- Do not find any noticeable bias in residuals w.r.t. distance, magnitude or depth (not shown).
- Note that decrease in variability w.r.t. magnitude is only apparent for frequencies $< 1\,\text{Hz}$.
- Discuss observed dependence of, particularly high-frequency, ground motions on focal depth.

2.213 Liu & Tsai (2005)

- Ground-motion model is:

$$\ln Y = a\ln(X+h) + bX + cM_w + d$$

where Y is in $\mathrm{cm/s^2}$ for horizontal PGA (for whole Taiwan) $a = -0.852$, $b = -0.0071$, $c = 1.027$, $d = 1.062$, $h = 1.24\,\mathrm{km}$ and $\sigma = 0.719$ and for vertical PGA (for whole Taiwan) $a = -1.340$, $b = -0.0036$, $c = 1.101$, $d = 1.697$, $h = 1.62\,\mathrm{km}$ and $\sigma = 0.687$. Also report coefficients for equations derived for three different sub-regions.

- Do not differentiate site conditions.
- Focal depths, h, between 2.72 and $29.98\,\mathrm{km}$.
- Data from high-quality digital strong-motion networks of Taiwan Strong Motion Instrumentation Program (TSMIP) and Central Mountain Strong Motion Array (CMSMA).
- Select data from earthquakes with $h \leq 30\,\mathrm{km}$ and with records from ≥ 6 stations at $d_e \leq 20\,\mathrm{km}$.
- Select events following the 1999 Chi-Chi earthquake ($M_w 7.7$) with $M_L > 6$.
- Do not use data from the Chi-Chi earthquake because: a) earlier analysis of Chi-Chi data showed short-period ground motion was significantly lower than expected and b) the Chi-Chi rupture triggered two $M6$ events on other faults thereby contaminating the ground motions recorded at some stations.
- Data uniformly distributed for $M_w \leq 6.5$ and $20 \leq r_{hypo} \leq 100\,\mathrm{km}$. Significant number of records for $r_{hypo} > 100\,\mathrm{km}$.
- Use data from the Chi-Chi earthquake and the 2003 Cheng-Kung earthquake ($M_w 6.8$) for testing applicability of developed equations.
- For 32 earthquakes (mainly with $M_w < 5.3$) convert M_L to M_w using empirical equation developed for Taiwan.
- Develop regional equations for three regions: CHY in SW Taiwan (16 earthquakes, 1382 records), IWA in NE Taiwan (14 earthquakes, 2105 records) and NTO in central Taiwan (13 earthquakes, 3671 records) and for whole Taiwan to compare regional differences of source clustering in ground-motion characteristics.
- Use M_w since corresponds to well-defined physical properties of the source, also it can be related directly to slip rate on faults and avoids saturation problems of other M-scales.
- Use relocated focal depths and epicentral locations.
- Do not use r_{jb} or r_{rup} because insufficient information on rupture geometries, particularly those of small earthquakes, even though believe such distance metrics are justified. However, for small earthquakes do not think using r_{hypo} rather than r_{rup} will introduce significant bias into the equations. Also use r_{hypo} because it is quickly determined after an earthquake hence early ground-motion maps can be produced.

- From equations derived for different sub-regions and from site residual contour maps that ground motions in CHY are about four times higher than elsewhere due to thick, recent alluvial deposits.
- Find predictions for Chi-Chi and Cheng-Kung PGAs are close to observations.
- Plot contour maps of residuals for different sites and relate the results to local geology (alluvial plains and valleys and high-density schist).
- Divide site residuals into three classes: $> 0.2\sigma$, -0.2–0.2σ and $< -0.2\sigma$ for four NEHRP-like site classes. Find the distribution of residuals is related to the site class particularly for the softest class. Find residuals for C (very dense soil and soft rock) and D (stiff soil) are similar so suggest combining them. Believe geomorphology may also play an important role in site classification because a geomorphologic unit is often closely related to a geologic unit.

2.214 McGarr & Fletcher (2005)

- Ground-motion model is:

$$\log(y) = a + bM + d\log(R) + kR + s_1 + s_2$$

  where y is in $\mathrm{cm/s^2}$, $a = -0.9892$, $b = 0.8824$, $d = -1.355$, $k = -0.1363$, $s_1 = 0.337$ (for stations on surface), $s_2 = 0$ (for station at depth) and $\sigma = 0.483$.
- Use data from seven stations, one of which (TU1) is located underground within the mine. Determine site factors (constrained to be between 0 and 1) from PGV data. Originally group into three site categories: one for stations with close to horizontal straight-line ray paths, one for stations with steeper ray paths and one for underground station. Find site factors for first two categories similar so combine, partly because there is no precedent for topographic site factors in empirical ground-motion estimation equations. Believe that low site factors found are because stations are on solid rock $V_s > 1.5\,\mathrm{km/s}$.
- Most data from Trail Mountain coal mine from between 12/2000 and 03/2001 (maximum $M_{CL}2.17$). Supplement with data (2 records) from a $M4.2$ earthquake at Willow Creak mine to provide data at much higher magnitude.
- Most data from $M_w < 1.7$.
- Lower magnitude limit dictated by need for adequate signal-to-noise ratio.
- Focal depths between 50 and $720\,\mathrm{m}$ (relative to the ground surface).
- Note that although data may be poorly suited to determine both d and k simultaneously they are retained because both attenuation mechanisms must be operative. State that d and k should be solely considered as empirical parameters due to trade-offs during fitting.
- Do not include a quadratic M term because it is generally of little consequence.
- Use r_{hypo} because earthquakes are small compared to distances so can be considered as point sources.
- Selected events using these criteria:

  - event was recorded by ≥ 6 stations;
  - data had high signal-to-noise ratio;
  - to obtain the broadest M-range as possible; and
  - to have a broad distribution of epicentral locations.

- Find that M_w (estimated for 6 events) does not significantly differ from M_{CL}.
- Find that constrains must be applied to coefficients. Constrain k to range -2–0 because otherwise find small positive values. Believe that this is because data inadequate for independently determining d and k.

2.215 Nowroozi (2005)

- Ground-motion model is:

$$\ln(A) = c_1 + c_2(M-6) + c_3 \ln(\sqrt{\mathrm{EPD}^2 + h^2}) + c_4 S$$

  where A is in $\mathrm{cm/s^2}$, $c_1 = 7.969$, $c_2 = 1.220$, $c_3 = -1.131$, $c_4 = 0.212$, $h = 10\,\mathrm{km}$ (fixed after tests) and $\sigma = 0.825$ for horizontal PGA and $c_1 = 7.262$, $c_2 = 1.214$, $c_3 = -1.094$[9], $c_4 = 0.103$, $h = 10\,\mathrm{km}$ (fixed after tests) and $\sigma = 0.773$ for vertical PGA.

- Uses four site categories (S equals number of site category):

  1. Rock. 117 records.
  2. Alluvial. 52 records.
  3. Gravel and sandy. 70 records.
  4. Soft. 39 records.

  Does analysis combining 1 and 2 together in a firm rock category ($S = 0$) and 3 and 4 in a soft soil category ($S = 1$) and for all site categories combined. Reports coefficients for these two tests.

- Focal depths between 9 and $73\,\mathrm{km}$. Most depths are shallow (depths fixed at $33\,\mathrm{km}$) and majority are about $10\,\mathrm{km}$. Does not use depth as independent parameter due to uncertainties in depths.
- Uses M_w because nearly all reported Ground-motion models use M_w.
- Uses macroseismic distance for three events since no r_{epi} reported.
- Believes that methods other than vectorial sum of both horizontal PGAs underestimates true PGA that acts on the structure. Notes that vectorial sum ideally requires that PGAs on the two components arrive at the same time but due to unknown or inaccurate timing the occurrence time cannot be used to compute the resolved component.
- Does not consider faulting mechanism due to lack of information for many events.
- Most records from $M_w \leq 5$.
- Originally includes terms $c_5(M-6)^2$ and $c_6\mathrm{EPD}$ but finds them statistically insignificant so drops them.

[9]There is a typographical error in Equation 12 of Nowroozi (2005) since this coefficient is reported as -1094.

- Notes that all coefficients pass the t-test of significance but that the site coefficients are not highly significant, which relates to poor site classification for some stations.
- Compares observed and predicted PGAs with respect to distance. Notes that match to observations is relatively good.
- Compares observed PGAs during Bam 2003 earthquake to those predicted and finds good match.

2.216 Ruiz & Saragoni (2005)

- Ground-motion model is:

$$x = \frac{A\mathrm{e}^{BM}}{(R + C)^D}$$

where x is in $\mathrm{cm/s^2}$, $A = 4$, $B = 1.3$, $C = 30$ and $D = 1.43$ for horizontal PGA, hard rock sites and thrust earthquakes; $A = 2$, $B = 1.28$, $C = 30$ and $D = 1.09$ for horizontal PGA, rock and hard soil sites and thrust earthquakes; $A = 11$, $B = 1.11$, $C = 30$, $D = 1.41$ for vertical PGA, hard rock sites and thrust earthquakes; $A = 18$, $B = 1.31$, $C = 30$, $D = 1.65$ for vertical PGA, rock and hard soil sites and thrust earthquakes; $A = 3840$, $B = 1.2$, $C = 80$ and $D = 2.16$ for horizontal PGA, rock and hard soil sites and intermediate-depth earthquakes; and $A = 66687596$, $B = 1.2$, $C = 80$ and $D = 4.09$ for vertical PGA, rock and hard soil sites and intermediate-depth earthquakes.

- Use two site categories:

Hard rock $V_s > 1500\,\mathrm{m/s}$. 8 records.

Rock and hard soil $360 < V_s < 1500\,\mathrm{m/s}$. 41 records.

- Focal depths between 28.8 and $50.0\,\mathrm{km}$.
- Develop separate equations for interface and intraslab (intermediate-depth) events.
- Baseline correct and bandpass filter (fourth-order Butterworth) with cut-offs 0.167 and $25\,\mathrm{Hz}$.
- 8 records from between $M_s 6.0$ and 7.0, 13 from between 7.0 and 7.5 and 20 from between 7.5 and 8.0.
- Values of coefficient D taken from previous studies.

2.217 Takahashi *et al.* (2005), Zhao *et al.* (2006) and Fukushima *et al.* (2006)

- Ground-motion model is:

$$\log_e(y) = aM_w + bx - \log_e(r) + e(h - h_c)\delta_h + F_R + S_I + S_S + S_{SL}\log_e(x) + C_k$$
$$\text{where} \quad r = x + c\exp(dM_w)$$

where y is in $\mathrm{cm/s^2}$, $\delta_h = 1$ when $h \geq h_c$ and 0 otherwise, $a = 1.101$, $b = -0.00564$, $c = 0.0055$, $d = 1.080$, $e = 0.01412$, $S_R = 0.251$, $S_I = 0.000$, $S_S = 2.607$, $S_{SL} =$

-0.528, $C_H = 0.293$, $C_1 = 1.111$, $C_2 = 1.344$, $C_3 = 1.355$, $C_4 = 1.420$, $\sigma = 0.604$ (intra-event) and $\tau = 0.398$ (inter-event). Use $h_c = 15\,\mathrm{km}$ because best depth effect for shallow events.

- Use five site classes (T is natural period of site):

Hard rock NEHRP site class A, $V_{s,30} > 1100\,\mathrm{m/s}$. 93 records. Use C_H.

SC I Rock, NEHRP site classes A+B, $600 < V_{s,30} \leq 1100\,\mathrm{m/s}$, $T < 0.2\,\mathrm{s}$. 1494 records. Use C_1.

SC II Hard soil, NEHRP site class C, $300 < V_{s,30} \leq 600\,\mathrm{m/s}$, $0.2 \leq T < 0.4\,\mathrm{s}$. 1551 records. Use C_2.

SC III Medium soil, NEHRP site class D, $200 < V_{s,30} \leq 300\,\mathrm{m/s}$, $0.4 \leq T < 0.6\,\mathrm{s}$. 629 records. Use C_3.

SC IV Soft soil, NEHRP site classes E+F, $V_{s,30} \leq 200\,\mathrm{m/s}$, $T \geq 0.6\,\mathrm{s}$. 989 records. Use C_4.

Site class unknown for 63 records.

- Focal depths, h, between about 0 and $25\,\mathrm{km}$ for crustal events, between about 10 and $50\,\mathrm{km}$ for interface events, and about 15 and $162\,\mathrm{km}$ for intraslab events. For earthquakes with $h > 125\,\mathrm{km}$ use $h = 125\,\mathrm{km}$.

- Classify events into three source types:

  1. Crustal.
  2. Interface. Use S_I.
  3. Slab. Use S_S and S_{SL}.

  and into four mechanisms using rake angle of $\pm 45°$ as limit between dip-slip and strike-slip earthquakes except for a few events where bounds slightly modified:

  1. Reverse. Use F_R if also crustal event.
  2. Strike-slip
  3. Normal
  4. Unknown

  Distribution of records by source type, faulting mechanism and region is given in following table.

Region	Focal Mechanism	Crustal	Interface	Slab	Total
Japan	Reverse	250	1492	408	2150
	Strike-slip	1011	13	574	1598
	Normal	24	3	735	762
	Unknown			8	8
	Total	1285	1508	1725	4518
Iran and Western USA	Reverse	123	12		135
	Strike-slip	73			73
	Total	196	12		208
All	Total	1481	1520	1725	4726

- Exclude data from distances larger than a magnitude-dependent distance ($300\,\mathrm{km}$ for intraslab events) to eliminate bias introduced by untriggered instruments.

- Only few records from $< 30\,\mathrm{km}$ and all from $< 10\,\mathrm{km}$ from 1995 Kobe and 2000 Tottori earthquake. Therefore add records from overseas from $< 40\,\mathrm{km}$ to constrain near-source behaviour. Note that could affect inter-event error but since only 20 earthquakes (out of 269 in total) added effect likely to be small.

- Do not include records from Mexico and Chile because Mexico is characterised as a 'weak' coupling zone and Chile is characterised as a 'strong' coupling zone (the two extremes of subduction zone characteristics), which could be very different than those in Japan.

- Note reasonably good distribution w.r.t. magnitude and depth.

- State that small number of records from normal faulting events does not warrant them between considered as a separate group.

- Note that number of records from each event varies greatly.

- Process all Japanese records in a consistent manner. First correct for instrument response. Next low-pass filter with cut-offs at $24.5\,\mathrm{Hz}$ for 50 samples-per-second data and $33\,\mathrm{Hz}$ for 100 samples-per-second data. Find that this step does not noticeably affect short period motions. Next determine location of other end of usable period range. Note that this is difficult due to lack of estimates of recording noise. Use the following procedure to select cut-off:

  1. Visually inspect acceleration time-histories to detect faulty recordings, S-wave triggers or multiple events.
  2. If record has relatively large values at beginning (P wave) and end of record, the record was mirrored and tapered for $5\,\mathrm{s}$ at each end.
  3. Append $5\,\mathrm{s}$ of zeros at both ends and calculate displacement time-history in frequency domain.
  4. Compare displacement amplitude within padded zeros to peak displacement within the record. If displacement in padded zeros was relatively large, apply a high-pass filter.
  5. Repeat using high-pass filters with increasing corner frequencies, f_c, until the displacement within padded zeros was 'small' (subjective judgement). Use $1/f_c$ found as maximum usable period.

  Verify method by using K-Net data that contains $10\,\mathrm{s}$ pre-event portions.

- Conduct extensive analysis on inter- and intra-event residuals. Find predictions are reasonably unbiased w.r.t. magnitude and distance for crustal and interface events and not seriously biased for slab events.

- Do not smooth coefficients.

- Do not impose constraints on coefficients. Check whether coefficient is statistically significant.

- Note that the assumption of the same anelastic attenuation coefficient for all types and depths of earthquakes could lead to variation in the anelastic attenuation rate in a manner that is not consistent with physical understanding of anelastic attenuation.
- Derive C_H using intra-event residuals for hard rock sites.
- Residual analyses show that assumption of the same magnitude scaling and near-source characteristics for all source types is reasonable and that residuals not not have a large linear trend w.r.t. magnitude. Find that introducing a magnitude-squared term reveals different magnitude scaling for different source types and a sizable reduction in inter-event error. Note that near-source behaviour mainly controlled by crustal data. Derive correction function from inter-event residuals of each earthquake source type separately to avoid trade-offs. Form of correction is: $\log_e(S_{MSst}) = P_{st}(M_w - M_C) + Q_{st}(M_w - M_C)^2 + W_{st}$. Derive using following three-step process:

  1. Fit inter-event residuals for earthquake type to a quadratic function of $M_w - M_C$ for all periods.
  2. Fit coefficients P_{st} for $(M_w - M_C)$ and Q_{st} for $(M_w - M_C)^2$ (from step 1) where subscript st denotes source types, to a function up to fourth oder of $\log_e(T)$ to get smoothed coefficients.
  3. Calculate mean values of differences between residuals and values of $P_{st}(M_w - M_C) + Q_{st}(M_w - M_C)^2$ for each earthquake, W_{st}, and fit mean values W_{st} to a function of $\log_e(T)$.

  For PGA $Q_C = W_C = Q_I = W_I = 0$, $\tau_C = 0.303$, $\tau_I = 0.308$, $P_S = 0.1392$, $Q_S = 0.1584$, $W_S = -0.0529$ and $\tau_S = 0.321$. Since magnitude-square term for crustal and interface is not significant at short periods when coefficient for magnitude-squared term is positive, set all coefficients to zero. Find similar predicted motions if coefficients for magnitude-squared terms derived simultaneously with other coefficients even though the coefficients are different than those found using the adopted two-stage approach.
- Compare predicted and observed motions normalized to $M_w 7$ and find good match for three source types and the different site conditions. Find model overpredicts some near-source ground motions from SC III and SC IV that is believed to be due to nonlinear effects.

2.218 Wald *et al.* (2005)

- Ground-motion model is:

$$\log_{10}(Y) = B_1 + B_2(M - 6) - B_5 \log_{10} R$$
$$\text{where} \quad R = \sqrt{R_{jb}^2 + 6^2}$$

  where Y is in $\mathrm{cm/s^2}$, $B_1 = 4.037$, $B_2 = 0.572$, $B_5 = 1.757$ and $\sigma = 0.836$.

2.219 Atkinson (2006)

- Ground-motion model is:

$$\log Y = c0 + c1(\mathbf{M} - 5) + c2(\mathbf{M} - 5)^2 + c3 \log R + c4R + S_i$$
$$R = \sqrt{d^2 + h^2}$$

where Y is in $\mathrm{m/s^2}$, $c0 = 2.007$, $c1 = 0.567$, $c2 = 0.0311$, $c3 = -1.472$, $c4 = 0.00000$, $h = 5\,\mathrm{km}$ [from Boore *et al.* (1997)], $\sigma(\mathrm{BJF}) = 0.309$, $\sigma(\mathrm{emp} - \mathrm{amp}) = 0.307$ and $\sigma(\mathrm{NoSiteCorr}) = 0.305$. Individual station: with empirical-corrected amplitudes $\sigma = 0.269$ and with BJF-corrected amplitudes $\sigma = 0.268$.

- Uses data from 21 TriNet stations with known $V_{s,30}$ values. $190 \leq V_{s,30} \leq 958\,\mathrm{m/s}$. Uses two approaches for site term S_i. In first method (denoted 'empirically-corrected amplitudes', $\mathrm{emp} - \mathrm{amp}$) uses empirical site amplification factors from previous study of TriNet stations (for PGA uses site factor for PSA at $0.3\,\mathrm{s}$ because correction for PGA is unavailable). In second method [denoted 'Boore-Joyner-Fumal (BJF)-corrected amplitudes', BJF] uses amplification factors based on $V_{s,30}$ from Boore *et al.* (1997) to correct observations to reference (arbitrarily selected) $V_{s,30} = 760\,\mathrm{m/s}$.
- Uses only data with amplitudes $> 0.01\%\,\mathrm{g}$ (100 times greater than resolution of data, $0.0001\%\,\mathrm{g}$).
- States that developed relations not intended for engineering applications due to lack of data from large events and from short distances. Equations developed for investigation of variability issues for which database limitations are not crucial.
- Many records from Landers mainshock and aftershocks.
- Uses standard linear regression since facilitates comparisons using regressions of different types of datasets, including single-station datasets.
- Notes possible complications to functional form due to effects such as magnitude-dependent shape are not important due to small source size of most events.
- Truncates data at $300\,\mathrm{km}$ to get dataset that is well distributed in distance-amplitude space.
- Notes that small differences between σs when no site correction is applied and when site correction is applied could be due to complex site response in Los Angeles basin.
- Fits trend-lines to residuals versus distance for each station and finds slope not significantly different from zero at most stations except for Osito Audit (OSI) (lying in mountains outside the geographical area defined by other stations), which has a significant positive trend.
- Finds empirical-amplification factors give better estimate of average site response (average residuals per station closer to zero) than $V_{s,30}$-based factors at short periods but the reverse for long periods. Notes $V_{s,30}$ gives more stable site-response estimates, with residuals for individual stations less than factor of 1.6 for most stations.
- Finds standard deviations of station residuals not unusually large at sites with large mean residual, indicating that average site response estimates could be improved.
- Plots standard deviation of station residuals using $V_{s,30}$-based factors and the average of these weighted by number of observations per station. Compares with standard deviation from entire databank. Finds that generally standard deviations of station residuals slightly lower (about 10%) than for entire databank.
- Examines standard deviations of residuals averaged over 0.5-unit magnitude bins and finds no apparent trend for $\mathbf{M}3.5$ to $\mathbf{M}7.0$ but notes lack of large magnitude data.

- Restricts data by magnitude range (e.g. $4 \leq \mathbf{M} \leq 6$) and/or distance (e.g. $\leq 80\,\mathrm{km}$) and find no reduction in standard deviation.

- Finds no reduction in standard deviation using one component rather than both.

- Performs separate analysis of residuals for Landers events (10 stations having ≥ 20 observations) recorded at $> 100\,\mathrm{km}$. Notes that due to similarity of source and path effects for a station this should represent a minimum in single-station σ. Finds σ of 0.18 ± 0.06.

2.220 Beyer & Bommer (2006)

- Exact functional form of Ground-motion model is not given but note includes linear and quadratic terms of magnitude and a geometric spreading term. Coefficients not given but report ratios of σ using different definitions w.r.t. σ using geometric mean.

- Distribution w.r.t. NEHRP site classes is:

A	8 records
B	37 records
C	358 records
D	534 records
E	11 records
Unspecified	1 record

- Use data from Next Generation Attenuation (NGA) database.

- Distribution w.r.t. mechanism is:

Strike-slip	333 records, 51 earthquakes
Normal	36 records, 12 earthquakes
Reverse	329 records, 21 earthquakes
Reverse-oblique	223 records, 9 earthquakes
Normal-oblique	25 records, 7 earthquakes
Undefined	3 records, 3 earthquakes

- Exclude records from Chi-Chi 1999 earthquake and its aftershocks to avoid bias due to over-representation of these data ($> 50\%$ of 3551 records of NGA databank).

- Exclude records with PGA (defined using geometric mean) $< 0.05\,\mathrm{g}$ to focus on motions of engineering significance and to avoid problems with resolution of analogue records.

- Exclude records with maximum usable period $< 0.5\,\mathrm{s}$.

- Exclude records without hypocentral depth estimate since use depth in regression analysis.

- Earthquakes contribute between 1 and 138 accelerograms.

- Note data is from wide range of M, d, mechanism, site class and instrument type.

- State aim was not to derive state-of-the-art Ground-motion models but to derive models with the same data and regression method for different component definitions.
- Assume ratios of σs from different models fairly insensitive to assumptions made during regression but that these assumptions affect σ values themselves.
- Find ratios of σs from using different definitions close to 1.
- Note that results should be applied with caution to subduction and stable continental regions since have not been checked against these data.

2.221 Bindi *et al.* (2006)

- Ground-motion model is for r_{epi}:

$$\log(y) = a + bM + c\log\sqrt{(R^2 + h^2)} + e_1 S_1 + e_2 S_2 + e_3 S_3 + e_4 S_4$$

  where y is in g, $a = -2.487$, $b = 0.534$, $c = -1.280$, $h = 3.94$, $e_1 = 0$, $e_2 = 0.365$, $e_3 = 0.065$, $e_4 = 0.053$, $\sigma_{\text{event}} = 0.117$ and $\sigma_{\text{record}} = 0.241$ (or alternatively $\sigma_{\text{station}} = 0.145$ and $\sigma_{\text{record}} = 0.232$). For r_{hypo}:

$$\log(y) = a + bM + c\log R_h + e_1 S_1 + e_2 S_2 + e_3 S_3 + e_4 S_4$$

  where y is in g, $a = -2.500$, $b = 0.544$, $c = -1.284$ and $\sigma = 0.292$ (do not report site coefficients for r_{hypo}).

- Use four site classes:

  $\mathrm{A_C}$ Lacustrine and alluvial deposits with thickness $> 30\,\mathrm{m}$ ($180 \le V_{s,30} < 360\,\mathrm{m/s}$). Sites in largest lacustrine plains in Umbria region. $S_4 = 1$ and others are zero.

  $\mathrm{B_C}$ Lacustrine and alluvial deposits with thickness 10–$30\,\mathrm{m}$ ($180 \le V_{s,30} < 360\,\mathrm{m/s}$). Sites in narrow alluvial plains or shallow basins. $S_3 = 1$ and others are zero.

  $\mathrm{C_E}$ Shallow debris or colluvial deposits (3–$10\,\mathrm{m}$) overlaying rock (surface layer with $V_s < 360\,\mathrm{m/s}$). Sites located on shallow colluvial covers or slope debris (maximum depth $10\,\mathrm{m}$) on gentle slopes. $S_2 = 1$ and others are zero.

  $\mathrm{D_A}$ Rock ($V_{s,30} > 800\,\mathrm{m/s}$). Sites on outcropping rock, or related morphologic features, such as rock crests and cliffs. $S_1 = 1$ and others are zero.

  Base classifications on recently collected detailed site information from site investigations, census data, topographic maps, data from previous reports on depth of bedrock, and data from public and private companies. Subscripts correspond to classification in Eurocode 8.

- Focal depths between 1.1 and $8.7\,\mathrm{km}$ except for one earthquake with depth $47.7\,\mathrm{km}$.
- Nearly all earthquakes have normal mechanism, with a few strike-slip earthquakes.
- Select earthquakes with $M_L \ge 4.0$ and $d < 100\,\mathrm{km}$.
- Use M_L since available for all events.
- Fault geometries only available for three events so use r_{epi} and r_{hypo} rather than r_{jb}. Note that except for a few records differences between r_{epi} and r_{jb} are small.

- Correct for baseline and instrument response and filter analogue records to remove high- and low-frequency noise by visually selecting a suitable frequency interval: average range was 0.5–$25\,\mathrm{Hz}$. Filter digital records with bandpass of, on average, 0.3–$40\,\mathrm{Hz}$.

- For $M_L < 5$ no records from $d_e > 50\,\mathrm{km}$.

- Use maximum-likelihood regression with event and record σs and also one with station and record σs. Perform each regression twice: once including site coefficients and once without to investigate reduction in σs when site information is included.

- Investigate difference in residuals for different stations when site coefficients are included or not. Find significant reductions in residuals for some sites, particularly for class $\mathrm{C_E}$.

- Note that some stations seem to display site-specific amplifications different than the general trend of sites within one site class. For these sites the residuals increase when site coefficients are introduced.

- Find large negative residuals for records from the deep earthquake.

- Find similar residuals for the four earthquakes not from the 1997–1998 Umbria-Marche sequence.

2.222 Campbell & Bozorgnia (2006a) and Campbell & Bozorgnia (2006b)

- Ground-motion model is:

$$
\begin{aligned}
\ln Y &= f_1(M) + f_2(R) + f_3(F) + f_4(\mathrm{HW}) + f_5(S) + f_6(D) \\
f_1(M) &= \begin{cases} c_0 + c_1 M & M \leq 5.5 \\ c_0 + c_1 M + c_2(M-5.5) & 5.5 < M \leq 6.5 \\ c_0 + c_1 M + c_2(M-5.5) + c_3(M-6.5) & M > 6.5 \end{cases} \\
f_2(R) &= (c_4 + c_5 M)\ln(\sqrt{r_{\mathrm{rup}}^2 + c_6^2}) \\
f_3(F) &= c_7 F_{\mathrm{RV}} f_F(H) + c_8 F_N \\
f_F(H) &= \begin{cases} H & H < 1\,\mathrm{km} \\ 1 & H \geq 1\,\mathrm{km} \end{cases} \\
f_4(\mathrm{HW}) &= c_9 F_{\mathrm{RV}} f_{\mathrm{HW}}(M) f_{\mathrm{HW}}(H) \\
f_{\mathrm{HW}}(R) &= \begin{cases} 1 & r_{\mathrm{jb}} = 0\,\mathrm{km} \\ 1 - (r_{\mathrm{jb}}/r_{\mathrm{rup}}) & r_{jb} > 0\,\mathrm{km} \end{cases} \\
f_{\mathrm{HW}}(M) &= \begin{cases} 0 & M \leq 6.0 \\ 2(M-6.0) & 6.0 < M < 6.5 \\ 1 & M \geq 6.5 \end{cases} \\
f_{\mathrm{HW}}(H) &= \begin{cases} 0 & H \geq 20\,\mathrm{km} \\ 1 - (H/20) & H < 20\,\mathrm{km} \end{cases} \\
f_5(S) &= \begin{cases} c_{10}\ln\left(\frac{V_{s30}}{k_1}\right) + k_2\left\{\ln\left[\mathrm{PGA}_r + c\left(\frac{V_{s30}}{k_1}\right)^n\right] - \ln[\mathrm{PGA}_r + c]\right\} & V_{s30} < k_1 \\ (c_{10} + k_2 n)\ln\left(\frac{V_{s30}}{k_1}\right) & V_{s30} \geq k_1 \end{cases} \\
f_6(D) &= \begin{cases} c_{11}(D-1) & D < 1\,\mathrm{km} \\ 0 & 1 \leq D \leq 3\,\mathrm{km} \\ c_{12}\{k_3[0.0000454 - \exp(-3.33D)] + k_4[0.472 - \exp(-0.25D)]\} & D > 3\,\mathrm{km} \end{cases}
\end{aligned}
$$

  Do not report coefficients, only display predicted ground motions. H is the depth to top of coseismic rupture in km, PGA_r is the reference value of PGA on rock with $V_{s30} = 1100\,\mathrm{m/s}$, D is depth to $2.5\,\mathrm{km/s}$ shear-wave velocity horizon (so-called sediment or basin depth) in km.

- Use V_{s30} (average shear-wave velocity in top $30\,\mathrm{m}$ in $\mathrm{m/s}$) to characterise site conditions.

- Model developed as part of PEER Next Generation Attenuation (NGA) project.

- State that model is not final and articles should be considered as progress reports.

- NGA database only includes records that represent free-field conditions (i.e. records from large buildings are excluded).

- Include earthquake if: 1) it occurred within the shallow continental lithosphere, 2) it was in a region considered to be tectonically active, 3) it had enough records to establish a reasonable source term and 4) it had generally reliable source parameters.

- Exclude records from earthquakes classified as poorly recorded defined by: $M < 5.0$ and $N < 5$, $5.0 \leq M < 6.0$ and $N < 3$ and $6.0 \leq M < 7.0$, $r_{\mathrm{rup}} > 60\,\mathrm{km}$ and $N < 2$

where N is number of records. Include singly-recorded earthquakes with $M \geq 7.0$ and $r_{\mathrm{rup}} \leq 60\,\mathrm{km}$ because of importance in constraining near-source estimates.

- Include records if: 1) it was from or near ground level, 2) it had negligible structural interaction effects and 3) it had generally reliable site parameters.

- Find two-step regression technique was much more stable than one-step method and allows the independent evaluation and modelling of ground-motion scaling effects at large magnitudes. Find random effects regression analysis gives very similar results to two-step method.

- Use classical data exploration techniques including analysis of residuals to develop functional forms. Develop forms using numerous iterations to capture observed trends. Select final forms based on: 1) their simplicity, although not an overriding factor, 2) their seismological bases, 3) their unbiased residuals and 4) their ability to be extrapolated to parameter values important for engineering applications (especially probabilistic seismic hazard analysis). Find that data did not always allow fully empirical development of functional form therefore apply theoretical constraints [coefficients n and c (period-independent) and k_i (period-dependent)].

- Use three faulting mechanisms:

$F_{\mathrm{RV}} = 1$, $F_{\mathrm{N}} = 0$ Reverse and reverse-oblique faulting,$30° < \lambda < 150°$, where λ is the average rake angle.

$F_{\mathrm{N}} = 1$, $F_{\mathrm{RV}} = 1$ Normal and normal-oblique faulting, $-150° < \lambda < -30°$.

$F_{\mathrm{RV}} = 0$, $F_{\mathrm{RV}} = 0$ Strike-slip, other λs.

- Find slight tendency for over-saturation of short-period ground motions at large magnitudes and short distances. Find other functional forms for magnitude dependence too difficult to constrain empirically or could not be reliably extrapolated to large magnitudes.

- Note transition depth for buried rupture ($1\,\mathrm{km}$) is somewhat arbitrary.

- Find weak but significant trend of increasing ground motion with dip for both reverse and strike-slip faults. Do not believe that seismological justified therefore do not include such a term.

- Nonlinear site model constrained by theoretical studies since empirical data insufficient to constrain complex nonlinear behaviour.

- Use depth to $2.5\,\mathrm{km/s}$ horizon because it showed strongest correlation with shallow and deep sediment-depth residuals.

- Believe that aspect ratio (ratio of rupture length to rupture width) has promise as a source parameter since it shows high correlation with residuals and could model change in ground-motion scaling at large magnitudes.

- Do not find standard deviations are magnitude-dependent. Believe difference with earlier conclusions due to larger number of high-quality intra-event recordings for both small and large earthquakes.

- Find standard deviation is dependent on level of ground shaking at soft sites.

2.223 Costa *et al.* (2006)

- Ground-motion model is:

$$\log_{10}(\mathrm{PGA}) = c_0 + c_1 M + c_2 M^2 + (c_3 + c_4 M)\log(\sqrt{d^2 + h^2}) + c_S S$$

  where PGA is in g, $c_0 = -3.879$, $c_1 = 1.178$, $c_2 = -0.068$, $c_3 = -2.063$, $c_4 = 0.102$, $c_S = 0.411$, $h = 7.8$ and $\sigma = 0.3448$ (for larger horizontal component), $c_0 = -3.401$, $c_1 = 1.140$, $c_2 = -0.070$, $c_3 = -2.356$, $c_4 = 0.150$, $c_S = 0.415$, $h = 8.2$ and $\sigma = 0.3415$ (for horizontal component using vectorial addition), $c_0 = -3.464$, $c_1 = 0.958$, $c_2 = -0.053$, $c_3 = -2.224$, $c_4 = 0.147$, $c_S = 0.330$, $h = 6.1$ and $\sigma = 0.3137$ (for vertical).

- Use two site classes (since do not have detailed information on geology at all considered stations):

$S = 0$ Rock

$S = 1$ Soil

- Use selection criteria: $3.0 \leq M \leq 6.5$ and $1 \leq d_e \leq 100\,\mathrm{km}$.

- Bandpass filter with cut-offs between 0.1 and $0.25\,\mathrm{Hz}$ and between 25 and $30\,\mathrm{Hz}$.

- Compute mean ratio between recorded and predicted motions at some stations of the RAF network. Find large ratios for some stations on soil and for some on rock.

2.224 Gómez-Soberón *et al.* (2006)

- Ground-motion model is:

$$\ln a = \alpha_0 + \alpha_1 M + \alpha_2 M^2 + \alpha_3 \ln R + \alpha_5 R$$

  where a is in $\mathrm{cm/s^2}$, $\alpha_0 = 1.237$, $\alpha_1 = 1.519$, $\alpha_2 = -0.0313$, $\alpha_3 = -0.844$, $\alpha_5 = -0.004$ and $\sigma = 0.780$.

- Exclude records from soft soil sites or with previously known site effects (amplification or deamplification).

- Focal depths between 5 and $80\,\mathrm{km}$.

- Also derive equation using functional form $\ln a = \alpha_0 + \alpha_1 M + \alpha_2 \ln R + \alpha_4 R$.

- Select records from stations located along the seismically active Mexican Pacific coast.

- Only use records from earthquakes with $M > 4.5$.

- Exclude data from normal faulting earthquakes using focal mechanisms, focal depths, location of epicentre and characteristics of records because subduction zone events are the most dominant and frequent type of earthquakes.

- Use M_w because consider best representation of energy release.

- Visually inspect records to exclude poor quality records.

- Exclude records from dams and buildings.
- Exclude records from 'slow' earthquakes, which produce smaller short-period ground motions.
- Correct accelerations by finding quadratic baseline to minimize the final velocity then filter using most appropriate bandpass filter (low cut-off frequencies between 0.05 and $0.4\,\mathrm{Hz}$ and high cut-off frequency of $30\,\mathrm{Hz}$).
- Use data from 105 stations: 7 in Chiapas, 6 in Oaxaca, 6 in Colima, 19 in Jalisco, 49 in Guerrero, 14 in Michoacán and 6 near the Michoacán-Guerrero border.

2.225 Hernandez *et al.* (2006)

- Ground-motion model is:

$$\log(y) = aM_L - \log(X) + bX + c_j$$

  where y is in $\mathrm{cm/s^2}$, $a = 0.41296$, $b = 0.0003$, $c_1 = 0.5120$, $c_2 = 0.3983$, $c_3 = 0.2576$, $c_4 = 0.1962$, $c_5 = 0.1129$ and $\sigma = 0.2331$.
- Data from ARM1 and ARM2 vertical borehole arrays of the Hualien LSST array at: surface (use c_1), $5.3\,\mathrm{m}$ (use c_2), $15.8\,\mathrm{m}$ (use c_3), $26.3\,\mathrm{m}$ (use c_4) and $52.6\,\mathrm{m}$ (use c_5). Surface geology at site is massive unconsolidated poorly bedded Pleistocene conglomerate composed of pebbles varying in diameter from 5 to $20\,\mathrm{cm}$, following $5\,\mathrm{m}$ is mainly composed of fine and medium sand followed by a gravel layer of $35\,\mathrm{m}$.
- Apply these criteria to achieve uniform data: $M_L > 5$, focal depth $< 30\,\mathrm{km}$ and $0.42M_L - \log(X + 0.02510^{0.42M_L} - 0.0033X + 1.22 > \log 10$ from a previous study.
- Most records from $M_L < 6$.
- Bandpass filter records with cut-offs at 0.08 and $40\,\mathrm{Hz}$.
- Propose $M_s = 1.154M_L - 1.34$.
- Some comparisons between records and predicted spectra are show for four groups of records and find a good match although for the group $M_L6.75$ and $X = 62\,\mathrm{km}$ find a slight overestimation, which believe is due to not modelling nonlinear magnitude dependence.
- Coefficients for vertical equations not reported.

2.226 Kanno *et al.* (2006)

- Ground-motion model is for $D \leq 30\,\mathrm{km}$:

$$\log \mathrm{pre} = a_1 M_w + b_1 X - \log(X + d_1 10^{0.5M_w}) + c_1$$

  and for $D > 30\,\mathrm{km}$:

$$\log \mathrm{pre} = a_2 M_w + b_2 X - \log(X) + c_2$$

  where pre is in $\mathrm{cm/s^2}$, $a_1 = 0.56$, $b_1 = -0.0031$, $c_1 = 0.26$, $d_1 = 0.0055$, $a_2 = 0.41$, $b_2 = -0.0039$, $c_2 = 1.56$, $\sigma_1 = 0.37$ and $\sigma_2 = 0.40$.

- Use $V_{s,30}$ to characterise site effects using correction formula: $G = \log(\mathrm{obs}/\mathrm{pre}) = p \log V_{s,30} + q$. Derive p and q by regression analysis on residuals averaged at intervals of every $100\,\mathrm{m/s}$ in $V_{s,30}$. $p = -0.55$ and $q = 1.35$ for PGA. Note that the equation without site correction predicts ground motions at sites with $V_{s,30} \approx 300\,\mathrm{m/s}$.

- Focal depths, D, for shallow events between $0\,\mathrm{km}$ and $30\,\mathrm{km}$ and for deep events between $30\,\mathrm{km}$ and about $180\,\mathrm{km}$.

- Note that it is difficult to determine a suitable model form due to large variability of strong-motion data, correlation among model variables and because of coupling of variables in the model. Therefore choose a simple model to predict average characteristics with minimum parameters.

- Introduce correction terms for site effects and regional anomalies.

- Originally collect 91731 records from 4967 Japanese earthquakes.

- Include foreign near-source data (from California and Turkey, which are compressional regimes similar to Japan) because insufficient from Japan.

- High-pass filter records with cut-off of $0.1\,\mathrm{Hz}$. Low-pass filter analogue records using cut-offs selected by visual inspection.

- Choose records where: 1) $M_w \geq 5.5$, 2) data from ground surface, 3) two orthogonal horizontal components available, 4) at least five stations triggered and 5) the record passed this M_w-dependent source distance criterion: $f(M_w, X) \geq \log 10$ (for data from mechanical seismometer networks) or $f(M_w, X) \geq \log 2$ (for data from other networks) where $f(M_w, X) = 0.42M_w - 0.0033X - \log(X + 0.02510^{0.43M_w}) + 1.22$ (from a consideration of triggering of instruments).

- Examine data distributions w.r.t. amplitude and distance for each magnitude. Exclude events with irregular distributions that could be associated with a particular geological/tectonic feature (such as volcanic earthquakes).

- Do not include data from Chi-Chi 1999 earthquake because have remarkably low amplitudes, which could be due to a much-fractured continental margin causing different seismic wave propagation than normal.

- Data from 2236 different sites in Japan and 305 in other countries.

- Note relatively few records from large and deep events.

- Note that maybe best to use stress drop to account for different source types (shallow, interface or intraslab) but cannot use since not available for all earthquakes in dataset.

- Investigate effect of depth on ground motions and find that ground-motions amplitudes from earthquakes with $D > 30\,\mathrm{km}$ are considerably different than from shallower events hence derive separate equations for shallow and deep events.

- Select 0.5 within function from earlier study.

- Weight regression for shallow events to give more weight to near-source data. Use weighting of 6.0 for $X \leq 25\,\mathrm{km}$, 3.0 for $25 < X \leq 50\,\mathrm{km}$, 1.5 for $50 < X \leq 75\,\mathrm{km}$ and 1.0 for $X > 75\,\mathrm{km}$. Note that weighting scheme has no physical meaning.

- Note that amplitude saturation at short distances for shallow model is controlled by crustal events hence region within several tens of kms of large ($M_w > 8.0$) interface events falls outside range of data.
- Note standard deviation decreases after site correction term is introduced.
- Introduce correction to model anomalous ground motions in NE Japan from intermediate and deep earthquakes occurring in the Pacific plate due to unique Q structure beneath the island arc. Correction is: $\log(\mathrm{obs/pre}) = (\alpha R_{\mathrm{tr}} + \beta)(D - 30)$ where R_{tr} is shortest distance from site to Kuril and Izu-Bonin trenches. α and β are derived by regression on subset fulfilling criteria: hypocentre in Pacific plate, station E of $137°$ E and station has $V_{s,30}$ measurement. For PGA $\alpha = -6.73 \times 10^{-5}$ and $\beta = 2.09 \times 10^{-2}$. Find considerable reduction in standard deviation after correction. Note that R_{tr} may not be the best parameter due to observed bias in residuals for deep events.
- Examine normalised observed ground motions w.r.t. predicted values and find good match.
- Examine residuals w.r.t. distance and predicted values. Find residuals decrease with increasing predicted amplitude and with decreasing distance. Note that this is desirable from engineering point of view, however, note that it may be due to insufficient data with large amplitudes and from short distances.
- Examine total, intra-event and inter-event residuals w.r.t. D for $D > 30\,\mathrm{km}$. When no correction terms are used, intra-event residuals are not biased but inter-event residuals are. Find mean values of total error increase up to $D = 70\,\mathrm{km}$ and then are constant. Find depth correction term reduces intra-event residuals considerably but increases inter-event error slightly. Overall bias improves for $D < 140\,\mathrm{km}$. Find site corrections have marginal effect on residuals.
- Find no bias in residuals w.r.t. magnitude.

2.227 Laouami *et al.* (2006)

- Ground-motion model is:

$$y = c \exp(\alpha M_s)[D^k + a]^{-\beta - \gamma R}$$

  where D is r_{hypo} and R is r_{epi}, y is in $\mathrm{m/s^2}$, $c = 0.38778$, $\alpha = 0.32927$, $k = 0.29202$, $a = 1.557574$, $\beta = 1.537231$, $\gamma = 0.027024$ and $\sigma = 0.03$ (note that this σ is additive).
- All records except one at $13\,\mathrm{km}$ from distances of 20 to $70\,\mathrm{km}$ so note that lack information from near field.
- Compare predictions to records from the 2003 Boumerdes ($M_w 6.8$) earthquake and find that it underpredicts the recorded motions, which note maybe due to local site effects.

2.228 Luzi *et al.* (2006)

- Ground-motion model is:

$$\log_{10} Y = a + bM + c \log_{10} R + s_{1,2}$$

Y is in g, $a = -4.417$, $b = 0.770$, $c = -1.097$, $s_1 = 0$, $s_2 = 0.123$, $\sigma_{\text{event}} = 0.069$ and $\sigma_{\text{record}} = 0.339$ (for horizontal PGA assuming intra-event σ), $a = -4.367$, $b = 0.774$, $c = -1.146$, $s_1 = 0$, $s_2 = 0.119$, $\sigma_{\text{station}} = 0.077$ and $\sigma_{\text{record}} = 0.337$ (for horizontal PGA assuming intra-station σ), $a = -4.128$, $b = 0.722$,$c = -1.250$, $s_1 = 0$, $s_2 = 0.096$, $\sigma_{\text{event}} = 0.085$ and $\sigma_{\text{record}} = 0.338$ (for vertical PGA assuming intra-event σ), $a = -4.066$, $b = 0.729$, $c = -1.322$, $s_1 = 0$, $s_2 = 0.090$, $\sigma_{\text{station}} = 0.105$ and $\sigma_{\text{record}} = 0.335$ (for vertical PGA assuming intra-station σ).

- Use two site classes:

  1. Rock, where $V_s > 800\,\text{m/s}$. Use s_1.
  2. Soil, where $V_s < 800\,\text{m/s}$. This includes all kinds of superficial deposits from weak rock to alluvial deposits. Use s_2.

  Can only use two classes due to limited information.

- Use 195 accelerometric records from 51 earthquakes ($2.5 \leq M_L \leq 5.4$) from 29 sites. Most records are from rock or stiff sites. Most data from $r_{hypo} < 50\,\text{km}$ with few from $> 100\,\text{km}$. Also use data from velocimeters (Lennartz 1 or $5\,\text{s}$ sensors and Guralp CMG-40Ts). In total 2895 records with $r_{hypo} < 50\,\text{km}$ from 78 events and 22 stations available, most from $20 \leq r_{hypo} \leq 30\,\text{km}$.

- For records from analogue instruments, baseline correct, correct for instrument response and bandpass filter with average cut-offs at 0.5 and $20\,\text{Hz}$ (after visual inspection of Fourier amplitude spectra). For records from digital instruments, baseline correct and bandpass filter with average cut-offs at 0.2 and $30\,\text{Hz}$. Sampling rate is $200\,\text{Hz}$. For records from velocimeters, correct for instrument response and bandpass filter with average cut-offs at 0.5 and $25\,\text{Hz}$. Sampling rate is $100\,\text{Hz}$.

- Select records from 37 stations with $10 \leq r_{hypo} \leq 50\,\text{km}$.

- Compare predictions and observations for $M_L 4.4$ and find acceptable agreement. Also find agreement between data from accelerometers and velocimeters.

2.229 Mahdavian (2006)

- Ground-motion model is:

$$\log(y) = a + bM + c\log(R) + dR$$

  where y is in cm/s^2. For horizontal PGA: $a = 1.861$, $b = 0.201$, $c = -0.554$, $d = -0.0091$ and $\sigma = 0.242$ (for Zagros, rock sites and $M_s \geq 4.5$ or $m_b \geq 5.0$), $a = 1.831$, $b = 0.208$, $c = -0.499$, $d = -0.0137$ and $\sigma = 0.242$ (for Zagros, rock sites and $3 < M_s < 4.6$ or $4.0 \leq m_b < 5.0$), $a = 2.058$, $b = 0.243$, $c = -1.02$, $d = -0.000875$ and $\sigma = 0.219$ (for central Iran and rock sites), $a = 2.213$, $b = 0.225$, $c = -0.847$, $d = -0.00918$ and $\sigma = 0.297$ (for Zagros and soil sites), $a = 1.912$, $b = 0.201$, $c = -0.790$, $d = -0.00253$ and $\sigma = 0.204$ (for central Iran and soil sites). For vertical PGA: $a = 2.272$, $b = 0.115$, $c = -0.853$, $d = -0.00529$ and $\sigma = 0.241$ (for Zagros, rock sites and $M_s \geq 4.5$ or $m_b \geq 5.0$), $a = 2.060$, $b = 0.147$[10], $c = -0.758$, $d = -0.00847$ and $\sigma = 0.270$ (for Zagros, rock sites and $M_s \geq 3.0$ or $m_b \geq 4.0$), $a = 1.864$, $b = 0.232$,

[10] Assume that 147 reported in paper is a typographical error.

$c = -1.049$, $d = -0.000372$ and $\sigma = 0.253$ (for central Iran and rock sites), $a = 2.251$, $b = 0.140$[11], $c = -0.822$, $d = -0.00734$ and $\sigma = 0.290$[12] (for Zagros and soil sites) and $a = 1.76$, $b = 0.232$[13], $c = -1.013$, $d = -0.000551$ and $\sigma = 0.229$ (for central Iran and soil sites).

- Uses two site classes:

  1. Sedimentary. 55 records.
  2. Rock. 95 records.

  Bases classification on geological maps, station visits, published classifications and shape of response spectra from strong-motion records. Notes that the classification could be incorrect for some stations. Uses only two classes to reduce possible errors.

- Divides Iran into two regions: Zagros and other areas.

- Select data with M_s or m_b where $m_b > 3.5$. Notes that only earthquakes with $m_b > 5.0$ are of engineering concern for Iran but since not enough data (especially for Zagros) includes smaller earthquakes.

- Use M_s when $m_b \geq 4$.

- Records bandpass filtered using Ormsby filters with cut-offs and roll-offs of 0.1–$0.25\,\mathrm{Hz}$ and 23–$25\,\mathrm{Hz}$.

- Notes that some data from far-field.

- Notes that some records do not feature the main portion of shaking.

- To be consistent, calculates r_{hypo} using S-P time difference. For some records P wave arrival time is unknown so use published hypocentral locations. Assumes focal depth of $10\,\mathrm{km}$ for small and moderate earthquakes and $15\,\mathrm{km}$ for large earthquakes.

- Does not recommend use of relation for Zagros and soil sites due to lack of data (15 records) and large σ.

- Compares recorded and predicted motions for some ranges of magnitudes and concludes that they are similar.

2.230 McVerry *et al.* (2006)

- Ground-motion model for crustal earthquakes is:

$$\begin{aligned}\ln \mathrm{SA}'_{A/B}(T) &= C'_1(T) + C_{4AS}(M-6) + C_{3AS}(T)(8.5-M)^2 + C'_5(T)r \\ &\quad + [C'_8(T) + C_{6AS}(M-6)] \ln \sqrt{r^2 + C^2_{10AS}(T)} + C'_{46}(T)r_{VOL} \\ &\quad + C_{32}\mathrm{CN} + C_{33AS}(T)\mathrm{CR} + F_{HW}(M,r)\end{aligned}$$

[11] Assume that 0140 reported in paper is a typographical error.
[12] Assume that 0290 reported in paper is a typographical error.
[13] Assume that 0232 reported in paper is a typographical error.

Ground-motion model for subduction earthquakes is:

$$\begin{aligned}\ln \mathrm{SA}'_{A/B}(T) &= C'_{11}(T) + \{C_{12Y} + [C'_{15}(T) - C'_{17}(T)]C_{19Y}\}(M-6) \\ &+ C_{13Y}(T)(10-M)^3 + C'_{17}(T)\ln[r + C_{18Y}\exp(C_{19Y}M)] + C'_{20}(T)H_c \\ &+ C'_{24}(T)\mathrm{SI} + C'_{46}(T)r_{VOL}(1-\mathrm{DS})\end{aligned}$$

where $C'_{15}(T) = C_{17Y}(T)$. For both models:

$$\ln \mathrm{SA}'_{C,D}(T) = \ln \mathrm{SA}'_{A/B}(T) + C'_{29}(T)\delta_C + [C_{30AS}(T)\ln(\mathrm{PGA}'_{A/B} + 0.03) + C'_{43}(T)]\delta_D$$

where $\mathrm{PGA}'_{A/B} = \mathrm{SA}'_{A/B}(T=0)$. Final model given by:

$$\mathrm{SA}_{A/B,C,D}(T) = \mathrm{SA}'_{A/B,C,D}(T)(\mathrm{PGA}_{A/B,C,D}/\mathrm{PGA}'_{A/B,C,D})$$

where $\mathrm{SA}_{A/B,C,D}$ is in g, r_{VOL} is length in km of source-to-site path in volcanic zone and $F_{HW}(M,r)$ is hanging wall factor of Abrahamson & Silva (1997). Coefficients for PGA (larger component) are: $C_1 = 0.28815$, $C_3 = 0$, $C_4 = -0.14400$, $C_5 = -0.00967$, $C_6 = 0.17000$, $C_8 = -0.70494$, $C_{10} = 5.60000$, $C_{11} = 8.68354$, $C_{12} = 1.41400$, $C_{13} = 0$, $C_{15} = -2.552000$, $C_{17} = -2.56727$, $C_{18} = 1.78180$, $C_{19} = 0.55400$, $C_{20} = 0.01550$, $C_{24} = -0.50962$, $C_{29} = 0.30206$, $C_{30} = -0.23000$, $C_{32} = 0.20000$, $C_{33} = 0.26000$, $C_{43} = -0.31769$, $C_{46} = -0.03279$, $\sigma_{M6} = 0.4865$, $\sigma_{slope} = -0.1261$, where $\sigma = \sigma_{M6} + \sigma_{slope}(M_w - 6)$ for $5 < M_w < 7$, $\sigma = \sigma_{M6} - \sigma_{slope}$ for $M_w < 5$ and $\sigma = \sigma_{M6} + \sigma_{slope}$ for $M_w > 7$ (intra-event), and $\tau = 0.2687$ (inter-event). Coefficients for PGA' (larger component) are: $C_1 = 0.18130$, $C_3 = 0$, $C_4 = -0.14400$, $C_5 = -0.00846$, $C_6 = 0.17000$, $C_8 = -0.75519$, $C_{10} = 5.60000$, $C_{11} = 8.10697$, $C_{12} = 1.41400$, $C_{13} = 0$, $C_{15} = -2.552000$, $C_{17} = -2.48795$, $C_{18} = 1.78180$, $C_{19} = 0.55400$, $C_{20} = 0.01622$, $C_{24} = -0.41369$, $C_{29} = 0.44307$, $C_{30} = -0.23000$, $C_{32} = 0.20000$, $C_{33} = 0.26000$, $C_{43} = -0.29648$, $C_{46} = -0.03301$, $\sigma_{M6} = 0.5035$, $\sigma_{slope} = -0.0635$ and $\tau = 0.2598$.

- Use site classes (combine A and B together and do not use data from E):

  A Strong rock. Strong to extremely-strong rock with: a) unconfined compressive strength $> 50\,\mathrm{MPa}$, and b) $V_{s,30} > 1500\,\mathrm{m/s}$, and c) not underlain by materials with compressive strength $< 18\,\mathrm{MPa}$ or $V_s < 600\,\mathrm{m/s}$.

  B Rock. Rock with: a) compressive strength between 1 and $50\,\mathrm{MPa}$, and b) $V_{s,30} > 360\,\mathrm{m/s}$, and c) not underlain by materials having compressive strength $< 0.8\,\mathrm{MPa}$ or $V_s < 300\,\mathrm{m/s}$.

  C, $\delta_C = 1$, $\delta_D = 0$ Shallow soil sites. Sites that: a) are not class A, class B or class E sites, and b) have low-amplitude natural period, T, $\leq 0.6\,\mathrm{s}$, or c) have soil depths $\leq$ these depths:

	Soil type and description	Maximum soil depth (m)
Cohesive soil	Representative undrained shear strengths (kPa)	
Very soft	< 12.5	0
Soft	12.5–25	20
Firm	25–50	25
Stiff	50–100	40
Very stiff or hard	100–200	60
Cohesionless soil	Representative SPT N values	
Very loose	< 6	0
Loose dry	6–10	40
Medium dense	10–30	45
Dense	30–50	55
Very dense	> 50	60
Gravels	> 30	100

D, $\delta_D = 1$, $\delta_C = 0$ Deep or soft soil sites. Sites that: a) are not class A, class B or class E sites, and b) have a low-amplitude $T > 0.6\,\mathrm{s}$, or c) have soil depths > depths in table above, or c) are underlain by $< 10\,\mathrm{m}$ of soils with an undrained shear-strength $< 12.5\,\mathrm{kPa}$ or soils with SPT N-values < 6.

E Very soft soil sites. Sites with: a) $> 10\,\mathrm{m}$ of very soft soils with undrained shear-strength $< 12.5\,\mathrm{kPa}$, b) $> 10\,\mathrm{m}$ of soils with SPT N values < 6, c) $> 10\,\mathrm{m}$ of soils with $V_s < 150\,\mathrm{m/s}$, or d) $> 10\,\mathrm{m}$ combined depth of soils with properties as described in a), b) and c).

Categories based on classes in existing New Zealand Loadings Standard but modified following statistical analysis. Note advantage of using site categories related to those in loading standards. Site classifications based on site periods but generally categories from site descriptions.

- Classify earthquakes in three categories:

Crustal Earthquakes occurring in the shallow crust of overlying Australian plate. 24 earthquakes. Classify into:

Strike-slip $-33 \leq \lambda \leq 33°$, $147 \leq \lambda \leq 180°$ or $-180 \leq \lambda \leq -147°$ where λ is the rake. 6 earthquakes. Centroid depths, H_c, $4 \leq H_c \leq 13\,\mathrm{km}$. $5.20 \leq M_w \leq 6.31$. $\mathrm{CN} = 0$, $\mathrm{CR} = 0$.

Normal $-146 \leq \lambda \leq -34°$. 7 earthquakes. $7 \leq H_c \leq 17\,\mathrm{km}$. $5.27 \leq M_w \leq 7.09$. $\mathrm{CN} = -1$, $\mathrm{CR} = 0$.

Oblique-reverse $33 \leq \lambda \leq 66°$ or $124 \leq \lambda \leq 146°$. 3 earthquakes. $5 \leq H_c \leq 19\,\mathrm{km}$. $5.75 \leq M_w \leq 6.52$. $\mathrm{CR} = 0.5$, $\mathrm{CN} = 0$.

Reverse $67 \leq \lambda \leq 123°$. 8 earthquakes. $4 \leq H_c \leq 13\,\mathrm{km}$. $5.08 \leq M_w \leq 7.23$. $\mathrm{CR} = 1$, $\mathrm{CN} = 0$.

Interface Earthquake occurring on the interface between Pacific and Australian plates with $H_c < 50\,\mathrm{km}$. 5 reserve and 1 strike-slip with reverse component. Use data with $15 \leq H_c \leq 24\,\mathrm{km}$. Classify using location in 3D space. 6 earthquakes. $5.46 \leq M_w \leq 6.81$. $\mathrm{SI} = 1$, $\mathrm{DS} = 0$.

Slab Earthquakes occurring in slab source zone within the subducted Pacific plate. Predominant mechanism changes with depth. 19 earthquakes. $26 \leq H_c \leq 149\,\mathrm{km}$.

Split into shallow slab events with $H_c \leq 50\,\mathrm{km}$ (9 normal and 1 strike-slip, $5.17 \leq M_w \leq 6.23$) and deep slab events with $H_c > 50\,\mathrm{km}$ (6 reverse and 3 strike-slip, $5.30 \leq M_w \leq 6.69$). $\mathrm{SI} = 0$, $\mathrm{DS} = 1$ (for deep slab events).

Note seismicity cross sections not sufficient to distinguish between interface and slab events, also require source mechanism.

- Find that mechanism is not a significant extra parameter for motions from subduction earthquakes.
- State that model is not appropriate for source-to-site combinations where the propagation path is through the highly attenuating mantle wedge.
- Note magnitude range of New Zealand is limited with little data for large magnitudes and from short distances. Most data from $d > 50\,\mathrm{km}$ and $M_w < 6.5$.
- Only include records from earthquakes with available M_w estimates because correlations between M_L and M_w are poor for New Zealand earthquakes. Include two earthquakes without M_w values (M_s was converted to M_w) since they provide important data for locations within and just outside the Central Volcanic Region.
- Only include data with centroid depth, mechanism type, source-to-site distance and a description of site conditions.
- Only include records with PGA above these limits (dependent on resolution of instrument):
  1. Acceleroscopes (scratch-plates): $0.02\,\mathrm{g}$
  2. Mechanical-optical accelerographs: $0.01\,\mathrm{g}$
  3. Digital 12-bit accelerographs: $0.004\,\mathrm{g}$
  4. Digital 16-bit accelerographs: $0.0005\,\mathrm{g}$
- Exclude data from two sites: Athene A (topographic effect) and Hanmer Springs (site resonance at 1.5–$1.7\,\mathrm{Hz}$) that exhibit excessive amplifications for their site class.
- Exclude data from sites of class E (very soft soil sites with $\gtrsim 10\,\mathrm{m}$ of material with $V_s < 150\,\mathrm{m/s}$) to be consistent with Abrahamson & Silva (1997) and Youngs *et al.* (1997). Not excluded because of large amplifications but because spectra appear to have site-specific characteristics.
- Exclude records from bases of buildings with > 4 storeys because may have been influenced by structural response.
- Exclude data from very deep events with travel paths passing through the highly attenuating mantle were excluded.
- Only use response spectral ordinates for periods where they exceed the estimated noise levels of the combined recording and processing systems.
- Lack of data from near-source. Only 11 crustal records from distances $< 25\,\mathrm{km}$ with 7 of these from 3 stations. To constrain model at short distances include overseas PGA data using same criteria as used for New Zealand data. Note that these data were not intended to be comprehensive for 0–$10\,\mathrm{km}$ range but felt to be representative. Note that

it is possible New Zealand earthquakes may produce PGAs at short distances different that those observed elsewhere but feel that it is better to constrain the near-source behaviour rather than predict very high PGAs using an unconstrained model.

- In order to supplement limited data from moderate and high-strength rock and from the volcanic region, data from digital seismographs were added.
- Data corrected for instrument response.
- Derive model from 'base models' (other Ground-motion models for other regions). Select 'base model' using residual analyses of New Zealand data w.r.t. various models. Choose models of Abrahamson & Silva (1997) for crustal earthquakes and Youngs *et al.* (1997). Link these models together by common site response terms and standard deviations to get more robust coefficients.
- Apply constraints using 'base models' to coefficients that are reliant on data from magnitude, distance and other model parameters sparsely represented in the New Zealand data. Coefficients constrained are those affecting estimates in near-source region, source-mechanism terms for crustal earthquakes and hanging-wall terms. Eliminate some terms in 'base models' because little effect on measures of fit using Akaike Information Criterion (AIC).
- Apply the following procedure to derive model. Derive models for PGA and SA using only records with response spectra available (models with primed coefficients). Next derive model for PGA including records without response spectra (unprimed coefficients). Finally multiply model for SA by ratio between the PGA model using all data and that using only PGA data with corresponding response spectra. Apply this method since PGA estimates using complete dataset for some situations (notably on rock and deep soil and for near-source region) are higher than PGA estimates using reduced dataset and are more in line with those from models using western US data. This scaling introduces a bias in final model. Do not correct standard deviations of models for this bias.
- Use r_{rup} for 10 earthquakes and r_c for rest. For most records were r_c was used, state that it is unlikely model is sensitive to use r_c rather than r_{rup}. For five records discrepancy likely to be more than 10%.
- Free coefficients are: C_1, C_{11}, C_8, C_{17}, C_5, C_{46}, C_{20}, C_{24}, C_{29} and C_{43}. Other coefficients fixed during regression. Coefficients with subscript AS are from Abrahamson & Silva (1997) and those with subscript Y are from Youngs *et al.* (1997). Try varying some of these fixed coefficients but find little improvement in fits.
- State that models apply for $5.25 \leq M_w \leq 7.5$ and for distances $\leq 400\,\mathrm{km}$, which is roughly range covered by data.
- Note possible problems in applying model for $H_c > 150\,\mathrm{km}$ therefore suggest H_c is fixed to $150\,\mathrm{km}$ if applying model to deeper earthquakes.
- Note possible problems in applying model for $M_w < 5.25$.
- Apply constraints to coefficients to model magnitude- and distance-saturation.
- Try including an anelastic term for subduction earthquakes but find insignificant.

- Investigate possibility of different magnitude-dependence and attenuation rates for interface and slab earthquakes but this required extra parameters that are not justified by AIC.
- Investigate possible different depth dependence for interface and slab earthquakes but extra parameters not justified in terms of AIC.
- Try adding additive deep slab term but not significant according to AIC.
- Cannot statistically justify nonlinear site terms. Believe this could be due to lack of near-source records.
- Find that if a term is not included for volcanic path lengths then residuals for paths crossing the volcanic zone are increasingly negative with distance but this trend is removed when a volcanic path length term is included.
- Compare predictions to observed ground motions in 21/08/2003 Fiordland interface ($M_w 7.2$) earthquake and its aftershocks. Find ground motions, in general, underestimated.

2.231 Moss & Der Kiureghian (2006)

- Ground-motion model is [adopted from Boore *et al.* (1997)]:

$$\ln(Y) = \theta_1 + \theta_2(M_w - 6) + \theta_3(M_w - 6)^2 - \theta_4 \ln(\sqrt{R_{jb}^2 + \theta_5^2}) - \theta_6 \ln(V_{s,30}/\theta_7)$$

- Use $V_{s,30}$ to characterize site.
- Use data of Boore *et al.* (1997).
- Develop Bayesian regression method to account for parameter uncertainty in measured accelerations (due to orientation of instrument) (coefficient of variation of ~ 0.30, based on analysis of recorded motions) and magnitudes (coefficient of variation of ~ 0.10, based on analysis of reported M_w by various agencies) to better understand sources of uncertainty and to reduce model variance.
- Do not report coefficients. Only compare predictions with observations and with predictions by model of Boore *et al.* (1997) for $M_w 7.5$ and $V_{s,30} = 750\,\mathrm{m/s}$. Find slightly different coefficients than Boore *et al.* (1997) but reduced model standard deviations.

2.232 Pousse *et al.* (2006)

- Ground-motion model is:

$$\log_{10}(\mathrm{PGA}) = a_{\mathrm{PGA}} M + b_{\mathrm{PGA}} R - \log_{10}(R) + S_{\mathrm{PGA},k}, k = 1, 2, \ldots, 5$$

  where PGA is in $\mathrm{cm/s^2}$, $a_{\mathrm{PGA}} = 0.4346$, $b_{\mathrm{PGA}} = -0.002459$, $S_{\mathrm{PGA},1} = 0.9259$, $S_{\mathrm{PGA},2} = 0.9338$, $S_{\mathrm{PGA},3} = 0.9929$, $S_{\mathrm{PGA},4} = 0.9656$, $S_{\mathrm{PGA},5} = 0.9336$ and $\sigma = 0.2966$.

- Use five site categories (from Eurocode 8):

A $V_{s,30} > 800\,\mathrm{m/s}$. Use $S_{\mathrm{PGA},1}$. 43 stations, 396 records.

B $360 < V_{s,30} < 800\,\mathrm{m/s}$. Use $S_{\mathrm{PGA},2}$. 399 stations, 4190 records.

C $180 < V_{s,30} < 360\,\mathrm{m/s}$. Use $S_{\mathrm{PGA},3}$. 383 stations, 4108 records.

D $V_{s,30} < 180\,\mathrm{m/s}$. Use $S_{\mathrm{PGA},4}$. 65 stations, 644 records.

E Site D or C underlain in first $20\,\mathrm{m}$ with a stiffer layer of $V_s > 800\,\mathrm{m/s}$. Use $S_{\mathrm{PGA},5}$. 6 stations, 52 records.

Use statistical method of Boore (2004) with parameters derived from KiK-Net profiles in order to extend V_s profiles down to $30\,\mathrm{m}$ depth.

- Records from K-Net network whose digital stations have detailed geotechnical characterisation down to $20\,\mathrm{m}$ depth.
- Retain only records from events whose focal depths $< 25\,\mathrm{km}$.
- Convert M_{JMA} to M_w using empirical conversion formula to be consist with other studies.
- Apply magnitude-distance cut-off to exclude distant records.
- Bandpass filter all records with cut-offs 0.25 and $25\,\mathrm{Hz}$. Visually inspect records for glitches and to retain only main event if multiple events recorded.
- Find that one-stage maximum likelihood regression gives almost the same results.
- Also derive equations for other strong-motion parameters.

2.233 Souriau (2006)

- Ground-motion model is:

$$\log_{10}(\mathrm{PGA}) = a + bM + c\log_{10} R$$

where y is in $\mathrm{m/s^2}$, $a = -2.50 \pm 0.18$, $b = 0.99 \pm 0.05$ and $c = -2.22 \pm 0.08$ when $M = M_{\mathrm{LDG}}$ and $a = -2.55 \pm 0.19$, $b = 1.04 \pm 0.05$ and $c = -2.17 \pm 0.08$ when $M = M_{\mathrm{ReNass}}$ (σ is not given although notes that 'explained variance is of the order of 84%').

- Focal depths between 0 and $17\,\mathrm{km}$.
- Most data from $R < 200\,\mathrm{km}$.
- Uses PGAs from S-waves.
- Finds that introducing an anelastic attenuation term does not significantly improve explained variance because term is poorly constrained by data due to trade offs with geometric term and travel paths are short. When an anelastic term is introduced finds: $\log_{10}(\mathrm{PGA}) = -3.19(\pm 0.25) + 1.09(\pm 0.05)M_{\mathrm{ReNass}} - 1.83(\pm 0.12)\log_{10} R - 0.0013(\pm 0.0004)R$.

2.234 Zare & Sabzali (2006)

- Ground-motion model is:

$$\log \mathrm{Sa}(T) = a_1(T)M + a_2(T)M^2 + b(T)\log(R) + c_i(T)S_i$$

where Sa is in g, $a_1 = 0.5781$, $a_2 = -0.0317$, $b = -0.4352$, $c_1 = -2.6224$, $c_2 = -2.5154$, $c_3 = -2.4654$, $c_4 = -2.6213$ and $\sigma = 0.2768$ (for horizontal PGA), $a_1 = 0.5593$, $a_2 = -0.0258$, $b = -0.6119$, $c_1 = -2.6261$, $c_2 = -2.6667$, $c_3 = -2.5633$, $c_4 = -2.7346$ and $\sigma = 0.2961$ (for vertical PGA).

- Use four site classes based on fundamental frequency, f, from receiver functions:

Class 1 $f > 15\,\mathrm{Hz}$. Corresponds to rock and stiff sediment sites with $V_{s,30} > 700\,\mathrm{m/s}$. 22 records. $S_1 = 1$ and other $S_i = 0$.

Class 2 $5 < f \leq 15\,\mathrm{Hz}$. Corresponds to stiff sediments and/or soft rocks with $500 < V_{s,30} \leq 700\,\mathrm{m/s}$. 16 records. $S_2 = 1$ and other $S_i = 0$.

Class 3 $2 < f \leq 5\,\mathrm{Hz}$. Corresponds to alluvial sites with $300 < V \leq 500\,\mathrm{m/s}$. 25 records. $S_3 = 1$ and other $S_i = 0$.

Class 4 $f \leq 2\,\mathrm{Hz}$. Corresponds to thick soft alluvium. 26 records. $S_4 = 1$ and other $S_i = 0$.

- Separate records into four mechanisms: reverse (14 records), reverse/strike-slip (1 record), strike-slip (26 records) and unknown (48 records).
- Select records that have PGA $> 0.05\,\mathrm{g}$ on at least one component and are of good quality in frequency band of $0.3\,\mathrm{Hz}$ or less.
- Find results using one- or two-step regression techniques are similar. Only report results from one-step regression.
- M_w for earthquakes obtained directly from level of acceleration spectra plateau of records used.
- r_{hypo} for records obtained from S-P time difference.
- Most data from $r_{hypo} < 60\,\mathrm{km}$.
- Bandpass filter records with cut-offs of between 0.08 and $0.3\,\mathrm{Hz}$ and between 16 and $40\,\mathrm{Hz}$.
- Note that the lack of near-field data is a limitation.

2.235 Akkar & Bommer (2007b)

- Ground-motion model is:

$$\log y = b_1 + b_2 M + b_3 M^2 + (b_4 + b_5 M)\log\sqrt{R_{\mathrm{jb}}^2 + b_6^2} + b_7 S_S + b_8 S_A + b_9 F_N + b_{10} F_R$$

where y is in $\mathrm{cm/s^2}$, $b_1 = 1.647$, $b_2 = 0.767$, $b_3 = -0.074$, $b_4 = -3.162$, $b_5 = 0.321$, $b_6 = 7.682$, $b_7 = 0.105$, $b_8 = 0.020$, $b_9 = -0.045$, $b_{10} = 0.085$, $\sigma_1 = 0.557 - 0.049M$ (intra-event) and $\sigma_2 = 0.189 - 0.017M$ (inter-event) when b_3 is unconstrained and $b_1 = 4.185$, $b_2 = -0.112$, $b_4 = -2.963$, $b_5 = 0.290$, $b_6 = 7.593$, $b_7 = 0.099$, $b_8 = 0.020$, $b_9 = -0.034$, $b_{10} = 0.104$, $\sigma_1 = 0.557 - 0.049M$ (intra-event) and $\sigma_2 = 0.204 - 0.018M$ (inter-event) when b_3 is constrained to zero (to avoid super-saturation of PGA).

- Use three site categories:

Soft soil $S_S = 1$, $S_A = 0$.

Stiff soil $S_A = 1$, $S_S = 0$.

Rock $S_S = 0$, $S_A = 0$.

- Use three faulting mechanism categories:

Normal $F_N = 1$, $F_R = 0$.

Strike-slip $F_N = 0$, $F_R = 0$.

Reverse $F_R = 1$, $F_N = 0$.

- Use same data as Akkar & Bommer (2007a), which is similar to that used by Ambraseys *et al.* (2005a).
- Individually process records using well-defined correction procedure to select the cut-off frequencies (Akkar & Bommer, 2006).
- Use pure error analysis to determine magnitude dependence of inter- and intra-event variabilities before regression analysis.

2.236 Ghodrati Amiri *et al.* (2007a) & Ghodrati Amiri *et al.* (2007b)

- Ground-motion model is:

$$\ln y = C_1 + C_2 M_s + C_3 \ln[R + C_4 \exp(M_s)] + C_5 R$$

  where y is in $\mathrm{cm/s^2}$, $C_1 = 4.15$, $C_2 = 0.623$, $C_3 = -0.96$ and $\sigma = 0.478$ for horizontal PGA, rock sites and Alborz and central Iran; $C_1 = 3.46$, $C_2 = 0.635$, $C_3 = -0.996$ and $\sigma = 0.49$ for vertical PGA, rock sites and Alborz and central Iran; $C_1 = 3.65$, $C_2 = 0.678$, $C_2 = -0.95$ and $\sigma = 0.496$ for horizontal PGA, soil sites and Alborz and central Iran; $C_1 = 3.03$, $C_2 = 0.732$, $C_3 = -1.03$ and $\sigma = 0.53$ for vertical PGA, soil sites and Alborz and central Iran; $C_1 = 5.67$, $C_2 = 0.318$, $C_3 = -0.77$, $C_5 = -0.016$ and $\sigma = 0.52$ for horizontal PGA, rock sites and Zagros; $C_1 = 5.26$, $C_2 = 0.289$, $C_3 = -0.8$, $C_5 = -0.018$ and $\sigma = 0.468$ for vertical PGA, rock sites and Zagros; $C_1 = 5.51$, $C_2 = 0.55$, $C_3 = -1.31$ and $\sigma = 0.488$ for horizontal PGA, soil sites and Zagros; and $C_1 = 5.52$, $C_2 = 0.36$, $C_3 = -1.25$ and $\sigma = 0.474$ for vertical PGA, soil sites and Zagros. Constrain C_4 to zero for better convergence even though σs are higher.

- Use two site categories (derive individual equations for each):

Rock Roughly $V_s \geq 375\,\mathrm{m/s}$.

Soil Roughly $V_s < 375\,\mathrm{m/s}$.

- Divide Iran into two regions: Alborz and central Iran, and Zagros, based on tectonics and derive separate equations for each.
- Use S-P times to compute r_{hypo} for records for which it is unknown.
- Exclude data from earthquakes with $M_s \leq 4.5$ to remove less accurate data and since larger earthquakes more important for seismic hazard assessment purposes.

- Most records from $r_{hypo} > 50\,\mathrm{km}$.
- Exclude poor quality records.
- Instrument, baseline correct and bandpass filter records with cut-offs depending on instrument type and site class. For SSA-2 recommend: 0.15–$0.2\,\mathrm{Hz}$ and $30 - 33\,\mathrm{Hz}$ for rock records and 0.07–$0.2\,\mathrm{Hz}$ and 30–$33\,\mathrm{Hz}$ for soil records. For SMA-1 recommend: 0.15–$0.25\,\mathrm{Hz}$ and 20–$23\,\mathrm{Hz}$ for rock records and 0.15–$0.2\,\mathrm{Hz}$ and 20–$23\,\mathrm{Hz}$ for soil records. Apply trial and error based on magnitude, distance and velocity time-history to select cut-off frequencies.
- Test a number of different functional forms.
- Often find a positive (non-physical) value of C_5. Therefore, remove this term. Try removing records with $r_{hypo} > 100\,\mathrm{km}$ but find little difference and poor convergence due to limited data.
- Do not include term for faulting mechanism because such information not available for Iranian events.

2.237 Aydan (2007)

- Ground-motion model is:

$$a_{\max} = F(V_s)G(R,\theta)H(M)$$

- Characterises sites by V_s (shear-wave velocity).
- Considers effect of faulting mechanism.
- Considers angle between strike and station, θ.

2.238 Bindi *et al.* (2007)

- Ground-motion models are:

$$\log_{10} Y = a + bM + (c + dM)\log_{10} R_{\mathrm{hypo}} + s_{1,2}$$

where Y is in $\mathrm{m/s^2}$, $a = -1.4580$, $b = 0.4982$, $c = -2.3639$, $d = 0.1901$, $s_2 = 0.4683$, $\sigma_{\mathrm{eve}} = 0.0683$ (inter-event), $\sigma_{\mathrm{sta}} = 0.0694$ (inter-station) and $\sigma_{\mathrm{rec}} = 0.2949$ (record-to-record) for horizontal PGA; and $a = -1.3327$, $b = 0.4610$, $c = -2.4148$, $d = 0.1749$, $s_2 = 0.3094$, $\sigma_{\mathrm{eve}} = 0.1212$ (inter-event), $\sigma_{\mathrm{sta}} = 0.1217$ (inter-station) and $\sigma_{\mathrm{rec}} = 0.2656$ (record-to-record) for vertical PGA.

$$\log_{10} Y = a + bM + (c + dM)\log_{10}(R_{\mathrm{epi}}^2 + h^2)^{0.5} + s_{1,2}$$

where Y is in $\mathrm{m/s^2}$, $a = -2.0924$, $b = 0.5880$, $c = -1.9887$, $d = 0.1306$, $h = 3.8653$, $s_2 = 0.4623$, $\sigma_{\mathrm{eve}} = 0.0670$ (inter-event), $\sigma_{\mathrm{sta}} = 0.0681$ (inter-station) and $\sigma_{\mathrm{rec}} = 0.2839$ (record-to-record) for horizontal PGA; and $a = -1.8883$, $b = 0.5358$, $c = -2.0869$, $d = 0.1247$, $h = 4.8954$, $s_2 = 0.3046$, $\sigma_{\mathrm{eve}} = 0.1196$ (inter-event), $\sigma_{\mathrm{sta}} = 0.0696$ (inter-station) and $\sigma_{\mathrm{rec}} = 0.2762$ (record-to-record). Coefficients not reported in article but in electronic supplement.

- Use two site categories:

  s_1 Rock. Maximum amplification less than 2.5 (for accelerometric stations) or than 4.5 (for geophone stations). Amplification thresholds defined after some trials.

  s_2 Soil. Maximum amplification greater than thresholds defined above.

  Classify stations using generalized inversion technique.

- Focal depths between 5 and $15\,\mathrm{km}$.

- Use aftershocks from the 1999 Kocaeli ($M_w 7.4$) earthquake.

- Use data from 31 $1\,\mathrm{Hz}$ 24-bit geophones and 23 12-bit and 16-bit accelerometers. Records corrected for instrument response and bandpass filtered (fourth order Butterworth) with cut-offs 0.5 and $25\,\mathrm{Hz}$ for $M_L \leq 4.5$ and 0.1 and $25\,\mathrm{Hz}$ for $M_L > 4.5$. Find filters affect PGA by maximum 10%.

- Only 13 earthquakes have $M_L < 1.0$. Most data between have $1.5 < M_L < 5$ and from $10 \leq d_e \leq 140\,\mathrm{km}$.

- Geophone records from free-field stations and accelerometric data from ground floors of small buildings.

- Use r_{hypo} and r_{epi} since no evidence for surface ruptures from Turkey earthquakes with $M_L < 6$ and no systematic studies on the locations of the rupture planes for events used.

- Since most earthquakes are strike-slip do not include style-of-faulting factor.

- Find differences in inter-event σ when using M_L or M_w, which relate to frequency band used to compute M_L (about 1–$10\,\mathrm{Hz}$) compared to M_w (low frequencies), but find similar intra-event σs using the two different magnitudes, which expected since this σ not source-related.

- Investigate influence of stress drop on inter-event σ for horizontal PGA relations using r_{epi} and M_L or M_w. Find inter-event errors range from negative (low stress drop) to positive (high stress drop) depending on stress drop.

- Regress twice: firstly not considering site classification and secondly considering. Find site classification significantly reduces inter-station errors for velometric stations but inter-station errors for accelerometric stations less affected.

2.239 Bommer *et al.* (2007)

- Ground-motion model is:

$$\log_{10}[\mathrm{PSA}(T)] = b_1 + b_2 M_w + b_3 M_w^2 + (b_4 + b_5 M_w)\log_{10}\sqrt{R_{jb}^2 + b_6^2} + b_7 S_S + b_8 S_A + b_9 F_N + b_{10} F_R$$

  where $\mathrm{PSA}(T)$ is in $\mathrm{cm/s^2}$, $b_1 = 0.0031$, $b_2 = 1.0848$, $b_3 = -0.0835$, $b_4 = -2.4423$, $b_5 = 0.2081$, $b_6 = 8.0282$, $b_7 = 0.0781$, $b_8 = 0.0208$, $b_9 = -0.0292$, $b_{10} = 0.0963$, $\sigma_1 = 0.599 \pm 0.041 - 0.058 \pm 0.008 M_w$ (intra-event) and $\sigma_2 = 0.323 \pm 0.075 - 0.031 \pm 0.014 M_w$ (inter-event).

- Use three site categories:

Soft soil $V_{s,30} < 360\,\mathrm{m/s}$. $S_S = 1$, $S_A = 1$. 75 records from $3 \leq M_w < 5$.

Stiff soil $360 < V_{s,30} < 750\,\mathrm{m/s}$. $S_A = 1$, $S_S = 0$. 173 records from $3 \leq M_w < 5$.

Rock $V_{s,30} \geq 750\,\mathrm{m/s}$. $S_S = 0$, $S_A = 0$. 217 records from $3 \leq M_w < 5$.

- Use three faulting mechanism categories:

Normal $F_N = 1$, $F_R = 0$. 291 records from $3 \leq M_w < 5$.

Strike-slip $F_N = 0$, $F_R = 0$. 140 records from $3 \leq M_w < 5$.

Reverse $F_R = 1$, $F_N = 0$. 24 records from $3 \leq M_w < 5$. 12% of all records. Note that reverse events poorly represented.

- Investigate whether Ground-motion models can be extrapolated outside the magnitude range for which they were derived.

- Extend dataset of Akkar & Bommer (2007b) by adding data from earthquakes with $3 \leq M_w < 5$. Search ISESD for records from earthquakes with $M_w < 5$, known site class and known faulting mechanism. Find one record from a $M_w 2$ event but only 11 for events with $M_w < 3$ therefore use $M_w 3$ as lower limit. Select 465 records from 158 events with $3 \leq M_w < 5$. Many additional records from Greece (mainly singly-recorded events), Italy, Spain, Switzerland, Germany and France. Few additional records from Iran and Turkey.

- Data well distributed w.r.t. magnitude, distance and site class but for $M_w < 4$ data sparse for distances $> 40\,\mathrm{km}$.

- Additional data has been uniformly processed with cut-offs at 0.25 and $25\,\mathrm{Hz}$.

- Use same regression technique as Akkar & Bommer (2007b).

- Observe that equations predict expected behaviour of response spectra so conclude that equations are robust and reliable.

- Compare predicted ground motions with predictions from model of Akkar & Bommer (2007b) and find large differences, which they relate to the extrapolation of models outside their range of applicability.

- Investigate effect of different binning strategies for pure error analysis (Douglas & Smit, 2001). Derive weighting functions for published equations using bins of $2\,\mathrm{km} \times 0.2$ magnitude units and require three records per bin before computing σ. Repeat using $1\,\mathrm{km} \times 0.1$ unit bins. Find less bins allow computation of σ. Also repeat original analysis but require four or five records per bin. Find more robust estimates of σ but note that four or five records are still small samples. Also repeating using logarithmic rather than linear distance increments for bins since ground motions shown to mainly decay geometrically. For all different approaches find differences in computed magnitude dependence depending on binning scheme. None of the computed slopes are significant at 95% confidence level.

- Repeat analysis assuming no magnitude dependence of σ. Find predictions with this model are very similar to those assuming a magnitude-dependent σ.

- Find that compared to σs of Akkar & Bommer (2007b) that inter-event σs has greatly increased but that intra-event σs has not, which they relate to the uncertainty in the determination of M_w and other parameters for small earthquakes.
- Repeat analysis exclude data from (in turn) Greece, Italy, Spain and Switzerland to investigate importance of regional dependence on results. Find that results are insensitive to the exclusion of individual regional datasets.
- Compute residuals with respect to M_w for four regional datasets and find that only for Spain (the smallest set) is a significant difference to general results found.
- Examine total and intra-event residuals for evidence of soil nonlinearity. Find that evidence for nonlinearity is weak although the expected negative slopes are found. Conclude that insufficient data (and too crude site classification) to adjust the model for soil nonlinearity.
- Plot inter-event and intra-event residuals w.r.t. M_w and find no trend and hence conclude that new equations perform well for all magnitudes.
- Do not propose model for application in seismic hazard assessments.

2.240 Boore & Atkinson (2007) & Boore & Atkinson (2008)

- Ground-motion model is:

$$\begin{aligned}
\ln Y &= F_M(M) + F_D(R_{JB}, M) + F_S(V_{S30}, R_{JB}, M) \\
F_D(R_{JB}, M) &= [c_1 + c_2(M - M_{ref})] \ln(R/R_{ref}) + c_3(R - R_{ref}) \\
R &= \sqrt{R_{JB}^2 + h^2} \\
F_M(M) &= \begin{cases} e_1\mathrm{U} + e_2\mathrm{SS} + e_3\mathrm{NS} + e_4\mathrm{RS} + e_5(M - M_h) + \\ \quad e_6(M - M_h)^2 \quad \text{for} \quad M \le M_h \\ e_1\mathrm{U} + e_2\mathrm{SS} + e_3\mathrm{NS} + e_4\mathrm{RS} + e_7(M - M_h) \quad \text{for} \quad M > M_h \end{cases} \\
F_S &= F_{LIN} + F_{NL} \\
F_{LIN} &= b_{lin} \ln(V_{S30}/V_{ref}) \\
F_{NL} &= \begin{cases} b_{nl} \ln(\mathrm{pga_low}/0.1) \quad \text{for} \quad \mathrm{pga4nl} \le a_1 \\ b_{nl} \ln(\mathrm{pga_low}/0.1) + c[\ln(\mathrm{pga4nl}/a_1)]^2 + \\ \quad d[\ln(\mathrm{pga4nl}/a_1)]^3 \quad \text{for} \quad a_1 < \mathrm{pga4nl} \le a_2 \\ b_{nl} \ln(\mathrm{pga4nl}/0.1) \quad \text{for} \quad a_2 < \mathrm{pga4nl} \end{cases} \\
c &= (3\Delta y - b_{nl}\Delta x)/\Delta x^2 \\
d &= -(2\Delta y - b_{nl}\Delta x)/\Delta x^3 \\
\Delta x &= \ln(a_2/a_1) \\
\Delta y &= b_{nl} \ln(a_2/\mathrm{pga_low}) \\
b_{nl} &= \begin{cases} b_1 \quad \text{for} \quad V_{S30} \le V_1 \\ (b_1 - b_2)\ln(V_{S30}/V_2)/\ln(V_1/V_2) + b_2 \quad \text{for} \quad V_1 < V_{S30} \le V_2 \\ b_2 \ln(V_{S30}/V_{ref})/\ln(V_2/V_{ref}) \quad \text{for} \quad V_2 < V_{S30} < V_{ref} \\ 0.0 \quad \text{for} \quad V_{ref} \le V_{S30} \end{cases}
\end{aligned}$$

where Y is in g, $M_h = 6.75$ (hinge magnitude), $V_{ref} = 760\,\mathrm{m/s}$ (specified reference velocity corresponding to the NEHRP B/C boundary), $a_1 = 0.03\,\mathrm{g}$ (threshold for linear amplifcation), $a_2 = 0.09\,\mathrm{g}$ (threshold for nonlinear amplification), $\mathrm{pga\_low} = 0.06\,\mathrm{g}$ (for transition between linear and nonlinear behaviour), $\mathrm{pga4nl}$ is predicted PGA in g for V_{ref} with $F_S = 0$, $V_1 = 180\,\mathrm{m/s}$, $V_2 = 300\,\mathrm{m/s}$, $b_{lin} = -0.360$, $b_1 = -0.640$, $b_2 = -0.14$, $M_{ref} = 4.5$, $R_{ref} = 1\,\mathrm{km}$, $c_1 = -0.66050$, $c_2 = 0.11970$, $c_3 = -0.01151$, $h = 1.35$, $e_1 = -0.53804$, $e_2 = -0.50350$, $e_3 = -0.75472$, $e_4 = -0.50970$, $e_5 = 0.28805$, $e_6 = -0.10164$, $e_7 = 0.0$; $\sigma = 0.502$ (intra-event); $\tau_U = 0.265$, $\tau_M = 0.260$ (inter-event); $\sigma_{TU} = 0.566$, $\sigma_{TM} = 0.560$ (total).

- Characterise sites using V_{S30}. Believe equations applicable for $180 \leq V_{S30} \leq 1300\,\mathrm{m/s}$ (state that equations should not be applied for very hard rock sites, $V_{S30} \geq 1500\,\mathrm{m/s}$). Bulk of data from NEHRP C and D sites (soft rock and firm soil) and very few data from A sites (hard rock). Use three equations for nonlinear amplification: to prevent nonlinear amplification increasing indefinitely as $\mathrm{pga4nl}$ decreases and to smooth transition from linear to nonlinear behaviour. Equations for nonlinear site amplification simplified version of those of Choi & Stewart (2005) because believe NGA database insufficient to simultaneously determine all coefficients for nonlinear site equations and magnitude-distance scaling due to trade-offs between parameters. Note that implicit trade-offs involved and change in prescribed soil response equations would lead to change in derived magnitude-distance scaling.

- Focal depths between 2 and $31\,\mathrm{km}$ with most $< 20\,\mathrm{km}$.

- Use data from the PEER Next Generation Attenuation (NGA) Flatfile supplemented with additional data from three small events (2001 Anza $M4.92$, 2003 Big Bear City $M4.92$ and 2002 Yorba Linda $M4.27$) and the 2004 Parkfield earthquake, which were used only for a study of distance attenuation function but not the final regression (due to rules of NGA project).

- Use three faulting mechanism categories using P and T axes:

  SS Strike-slip. Plunges of T and P axes $< 40°$. 35 earthquakes. Dips between 55 and $90°$. $4.3 \leq M \leq 7.9$. $\mathrm{SS} = 1, \mathrm{U} = 0, \mathrm{NS} = 0, \mathrm{RS} = 0$.

  RS Reverse. Plunge of T axis $> 40°$. 12 earthquakes. Dips between 12 and $70°$. $5.6 \leq M \leq 7.6$. $\mathrm{RS} = 1, \mathrm{U} = 0, \mathrm{SS} = 0, \mathrm{NS} = 0$.

  NS Normal. Plunge of P axis $> 40°$. 11 earthquakes. Dips between 30 and $70°$. $5.3 \leq M \leq 6.9$. $\mathrm{NS} = 1, \mathrm{U} = 0, \mathrm{SS} = 0, \mathrm{RS} = 0$.

  Note that some advantages to using P and T axes to classify earthquakes but using categories based on rake angles with: within $30°$ of horizontal as strike-slip, from 30 to $150°$ as reverse and from $-30°$ to $-150°$ as normal, gives essentially the same classification. Also allow prediction of motions for unspecified ($\mathrm{U} = 1$, $\mathrm{SS} = 0$, $\mathrm{NS} = 0$, $\mathrm{RS} = 0$) mechanism (use σs and τs with subscript U otherwise use σs and τs with subscript M).

- Exclude records from obvious aftershocks because believe that spectral scaling of aftershocks could be different than that of mainshocks. Note that this cuts the dataset roughly in half.

- Exclude singly-recorded earthquakes.

- Note that possible bias due to lack of low-amplitude data (excluded due to non-triggering of instrument, non-digitisation of record or below the noise threshold used in determining low-cut filter frequencies). Distance to closest non-triggered station not available in NGA

Flatfile so cannot exclude records from beyond this distance. No information available that allows exclusion of records from digital accelerograms that could remove this bias. Hence note that obtained distance dependence for small earthquakes and long periods may be biased towards a decay that is less rapid than true decay.

- Use estimated R_{JB}s for earthquakes with unknown fault geometries.
- Lack of data at close distances for small earthquakes.
- Three events (1987 Whittier Narrows, 1994 Northridge and 1999 Chi-Chi) contribute large proportion of records (7%, 10% and 24%).
- Note that magnitude scaling better determined for strike-slip events, which circumvent using common magnitude scaling for all mechanisms.
- Seek simple functional forms with minimum required number of predictor variables. Started with simplest reasonable form and added complexity as demanded by comparisons between predicted and observed motions. Selection of functional form heavily guided by subjective inspection of nonparametric plots of data.
- Data clearly show that modelling of anelastic attenuation required for distances $> 80\,\mathrm{km}$ and that effective geometric spreading is dependent on magnitude. Therefore, introduce terms in the function to model these effects, which allows model to be used to $400\,\mathrm{km}$.
- Do not include factors for depth-to-top of rupture, hanging wall/footwall or basin depth because residual analysis does not clearly show that the introduction of these factors would improve the predictive capabilities of model on average.
- Models are data-driven and make little use of simulations.
- Believe that models provide a useful alternative to more complicated NGA models as they are easier to implement in many applications.
- Firstly correct ground motions to obtain equivalent observations for reference velocity of $760\,\mathrm{m/s}$ using site amplification equations using only data with $R_{JB} \leq 80\,\mathrm{km}$ and $V_{S30} > 360\,\mathrm{m/s}$. Then regress site-corrected observations to obtain F_D and F_M with $F_S = 0$. No smoothing of coefficients determined in regression (although some of the constrained coefficients were smoothed).
- Assume distance part of model applies for crustal tectonic regimes represented by NGA database. Believe that this is a reasonable initial approach. Test regional effects by examining residuals by region.
- Note that data sparse for $R_{JB} > 80\,\mathrm{km}$, especially for moderate events, and, therefore, difficult to obtain robust c_1 (slope) and c_3 (curvature) simultaneously. Therefore, use data from outside NGA database (three small events and 2004 Parkfield) to define c_3 and use these fixed values of c_3 within regression to determine other coefficients. To determine c_3 and h from the four-event dataset set c_1 equal to -0.5, -0.8 and -1.0 and $c_2 = 0$ if the inclusion of event terms c_0 for each event. Use c_3s when $c_1 = -0.8$ since it is a typical value for this parameter in previous studies. Find that c_3 and h are comparable to those in previous studies.
- Note that desirable to constrain h to avoid overlap in curves for large earthquakes at very close distances. Do this by initially performing regression with h as free parameter and then modifying h to avoid overlap.

- After h and c_3 have been constrained solve for c_1 and c_2.

- Constrain quadratic for magnitude scaling so that maximum not reached for $M < 8.5$ to prevent oversaturation. If maximum reached for $M < 8.5$ then perform two-segment regression hinged at M_h with quadratic for $M \leq M_h$ and linear for $M > M_h$. If slope of linear segment is negative then repeat regression by constraining slope above M_h to 0.0. Find that data generally indicates oversaturation but believe this effect is too extreme at present. M_h fixed by observation that ground motions at short periods do not get significantly larger with increasing magnitude.

- Plots of event terms (from first stage of regression) against M show that normal-faulting earthquakes have ground motions consistently below those of strike-slip and reverse events. Firstly group data from all fault types together and solved for e_1, e_5, e_6, e_7 and e_8 by setting e_2, e_3 and e_4 to 0.0. Then repeat regression fixing e_5, e_6, e_7 and e_8 to values obtained in first step to find e_2, e_3 and e_4.

- Examine residual plots and find no significant trends w.r.t. M, R_{JB} or V_{S30} although some small departures from a null residual.

- Examine event terms from first stage of regression against M and conclude functional form provides reasonable fit to near-source data.

- Examine event terms from first stage of regression against M for surface-slip and no-surface-slip earthquakes. Find that most surface-slip events correspond to large magnitudes and so any reduction in motions for surface-slip earthquakes will be mapped into reduced magnitude scaling. Examine event terms from strike-slip earthquakes (because both surface- and buried-slip events in same magnitude range) and find no indication of difference in event terms for surface-slip and no-surface-slip earthquakes. Conclude that no need to include dummy variables to account for this effect.

- Examine residuals for basin depth effects. Find that V_{S30} and basin depth are highly correlated and so any basin-depth effect will tend to be captured by empirically-determined site amplifications. To separate V_{S30} and basin-depth effects would require additional information or assumptions but since aiming for simplest equations no attempt made to break down separate effects. Examine residuals w.r.t. basin depth and find little dependence.

- Chi-Chi data forms significant fraction (24% for PGA) of data set. Repeat complete analysis without these data to examine their influence. Find that predictions are not dramatically different.

- Note that use of anelastic coefficients derived using data from four earthquakes in central and southern California is not optimal and could lead to inconsistencies in hs.

2.241 Campbell & Bozorgnia (2007), Campbell & Bozorgnia (2008b) & Campbell & Bozorgnia (2008a)

- Ground-motion model is:

$$
\begin{aligned}
\ln \hat{Y} &= f_{mag} + f_{dis} + f_{flt} + f_{hng} + f_{site} + f_{sed} \\
f_{mag} &= \begin{cases} c_0 + c_1 & \text{for} \quad M \leq 5.5 \\ c_0 + c_1 M + c_2(M - 5.5) & \text{for} \quad 5.5 < M \leq 6.5 \\ c_0 + c_1 M + c_2(M - 5.5) + c_3(M - 6.5) & \text{for} \quad M > 6.5 \end{cases} \\
f_{dis} &= (c_4 + c_5 M) \ln(\sqrt{R_{RUP}^2 + c_6^2}) \\
f_{flt} &= c_7 F_{RV} f_{flt,Z} + c_8 F_{NM} \\
f_{flt,Z} &= \begin{cases} Z_{TOR} & \text{for} \quad Z_{TOR} < 1 \\ 1 & \text{for} \quad Z_{TOR} \geq 1 \end{cases} \\
f_{hng} &= c_9 f_{hng,R} f_{hng,M} f_{hng,Z} f_{hng,\delta} \\
f_{hng,R} &= \begin{cases} 1 & \text{for} \quad R_{JB} = 0 \\ \{\max(R_{RUP}, \sqrt{R_{JB}^2 + 1}) - R_{JB}\}/ & \\ \quad \max(R_{RUP}, \sqrt{R_{JB}^2 + 1}) & \text{for} \quad R_{JB} > 0, Z_{TOR} < 1 \\ (R_{RUP} - R_{JB})/R_{RUP} & \text{for} \quad R_{JB} > 0, Z_{TOR} \geq 1 \end{cases} \\
f_{hng,M} &= \begin{cases} 0 & \text{for} \quad M \leq 6.0 \\ 2(M - 6.0) & \text{for} \quad 6.0 < M < 6.5 \\ 1 & \text{for} \quad M \geq 6.5 \end{cases} \\
f_{hng,Z} &= \begin{cases} 0 & \text{for} \quad Z_{TOR} \geq 20 \\ (20 - Z_{TOR})/20 & \text{for} \quad 0 \leq Z_{TOR} < 20 \end{cases} \\
f_{hng,\delta} &= \begin{cases} 1 & \text{for} \quad \delta \leq 70 \\ (90 - \delta)/20 & \text{for} \quad \delta > 70 \end{cases} \\
f_{site} &= \begin{cases} c_{10} \ln\left(\frac{V_{S30}}{k_1}\right) + k_2 \left\{\ln\left[A_{1100} + c\left(\frac{V_{S30}}{k_1}\right)^n\right] - \ln(A_{1100} + c)\right\} & \text{for} \quad V_{S30} < k_1 \\ (c_{10} + k_2 n) \ln\left(\frac{V_{S30}}{k_1}\right) & \text{for} \quad k_1 \leq V_{S30} < 1100 \\ (c_{10} + k_2 n) \ln\left(\frac{1100}{k_1}\right) & \text{for} \quad V_{S30} \geq 1100 \end{cases} \\
f_{sed} &= \begin{cases} c_{11}(Z_{2.5} - 1) & \text{for} \quad Z_{2.5} < 1 \\ 0 & \text{for} \quad 1 \leq Z_{2.5} \leq 3 \\ c_{12} k_3 \mathrm{e}^{-0.75}[1 - \mathrm{e}^{-0.25(Z_{2.5}-3)}] & \text{for} \quad Z_{2.5} > 3 \end{cases} \\
\sigma &= \sqrt{\sigma_{\ln Y}^2 + \sigma_{\ln AF}^2 + \alpha^2 \sigma_{\ln A_B}^2 + 2\alpha\rho\sigma_{\ln Y_B}\sigma_{\ln A_B}} \\
\alpha &= \begin{cases} k_2 A_{1100}\{[A_{1100} + c(V_{S30}/k_1)^n]^{-1} - (A_{1100} + c)^{-1}\} & \text{for} \quad V_{S30} < k_1 \\ 0 & \text{for} \quad V_{S30} \geq k_1 \end{cases}
\end{aligned}
$$

where Y is in g, $c_0 = -1.715$, $c_1 = 0.500$, $c_2 = -0.530$, $c_3 = -0.262$, $c_4 = -2.118$, $c_5 = 0.170$, $c_6 = 5.60$, $c_7 = 0.280$, $c_8 = -0.120$, $c_9 = 0.490$, $c_{10} = 1.058$, $c_{11} = 0.040$, $c_{12} = 0.610$, $k_1 = 865$, $k_2 = -1.186$, $k_3 = 1.839$, $\sigma_{\ln Y} = 0.478$ (intra-event), $\tau_{\ln Y} = 0.219$ (inter-event), $\sigma_C = 0.166$, $\sigma_T = 0.526$ (total), $\sigma_{Arb} = 0.551$ and $\rho = 1.000$ (correlation coefficient between intra-event residuals of ground-motion parameter of interest and PGA). $\sigma_{\ln Y_B} = (\sigma_{\ln Y}^2 - \sigma_{\ln AF}^2)^{1/2}$ is standard deviation at base of site profile. Assume that $\sigma_{\ln AF} \approx 0.3$ based on previous studies for deep soil sites. $\sigma_{Arb} = \sqrt{\sigma_T^2 + \sigma_C^2}$ for estimating aleatory uncertainty of arbitrary horizontal component.

- Characterise sites using V_{S30}. Account for nonlinear effects using A_{1100}, median estimated PGA on reference rock outcrop ($V_{S30} = 1100\,\mathrm{m/s}$) in g. Linear part of f_{site} is consistent with previous studies but with constraint for constant site term for $V_{S30} > 1100\,\mathrm{m/s}$ (based on residual analysis) even though limited data for $V_{S30} > 1100\,\mathrm{m/s}$. When only including linear part of shallow site response term find residuals clearly exhibit bias when plotted against rock PGA, A_{1100}. Find that residuals not sufficient to determine functional form for nonlinear amplification so use 1D equivalent-linear site response simulations to constrain form and coefficients. Believe model applicable for $V_{S30} = 150$–$1500\,\mathrm{m/s}$.

- Also use depth to $2.5\,\mathrm{km/s}$ shear-wave velocity horizon (basin or sediment depth) in km, $Z_{2.5}$. Deep-basin term modelled based on 3D simulations for Los Angeles, San Gabriel and San Fernando basins (southern California) calibrated empirically from residual analysis, since insufficient observational data for fully empirical study. Shallow-sediment effects based on analysis of residuals. Note high correlation between V_{S30} and $Z_{2.5}$. Provide relationships for predicting $Z_{2.5}$ based on other site parameters. Believe model applicable for $Z_{2.5} = 0$–$10\,\mathrm{km}$.

- Use three faulting mechanism categories based on rake angle, λ:

  RV Reverse and reverse-oblique. $30 < \lambda < 150°$. 17 earthquakes. $F_{RV} = 1$ and $F_{NM} = 0$.

  NM Normal and normal-oblique. $-150 < \lambda < -30°$. 11 earthquakes. $F_{NM} = 1$ and $F_{RV} = 0$.

  SS Strike-slip. All other rake angles. 36 earthquakes. $F_{RV} = 0$ and $F_{NM} = 0$.

- Use data from PEER Next Generation Attenuation (NGA) Flatfile.

- Select records of earthquakes located within shallow continental lithosphere (crust) in a region considered to be tectonically active from stations located at or near ground level and which exhibit no known embedment or topographic effects. Require that the earthquakes have sufficient records to reliably represent the mean horizontal ground motion (especially for small magnitude events) and that the earthquake and record is considered reliable.

- Exclude these data: 1) records with only one horizontal component or only a vertical component; 2) stations without a measured or estimated V_{S30}; 3) earthquakes without a rake angle, focal mechanism or plunge of the P- and T-axes; 4) earthquakes with the hypocentre or a significant amount of fault rupture located in lower crust, in oceanic plate or in a stable continental region; 5) LDGO records from the 1999 Düzce earthquake that are considered to be unreliable due to their spectral shapes; 6) records from instruments designated as low-quality from the 1999 Chi-Chi earthquake; 7) aftershocks but not triggered earthquakes such as the 1992 Big Bear earthquake; 8) earthquakes with too few records (N) in relation to its magnitude, defined as: a) $M < 5.0$ and $N < 5$, b) $5.0 \leq M < 6.0$ and $N < 3$, c) $6.0 \leq M < 7.0$, $R_{RUP} > 60\,\mathrm{km}$ and $N < 2$ (retain singly-recorded earthquakes with $M \geq 7.0$ and $R_{RUP} \leq 60\,\mathrm{km}$ because of their significance); 9) records considered to represent non-free-field site conditions, defined as instrument located in a) basement of building, b) below the ground surface, c) on a dam except the abutment; and 10) records with known topographic effects such as Pacoima Dam upper left abutment and Tarzana Cedar Hill Nursery.

- Functional forms developed or confirmed using classical data exploration techniques, such as analysis of residuals. Candidate functional forms developed using numerous iterations to capture the observed trends in the recorded ground motion data. Final functional forms selected according to: 1) sound seismological basis; 2) unbiased residuals; 3) ability to be extrapolated to magnitudes, distances and other explanatory variables that are important for use in engineering and seismology; and 4) simplicity, although this was not an overriding factor. Difficult to achieve because data did not always allow the functional forms of some explanatory variables to be developed empirically. Theoretical constraints were sometimes used to define the functional forms.

- Use two-stage maximum-likelihood method for model development but one-stage random-effects method for final regression.

- Also perform statistical analysis for converting between selected definition of horizontal component and other definitions.

- Include depth to top of coseismic rupture plane, Z_{TOR}, which find important for reverse-faulting events. Find that some strike-slip earthquakes with partial or weak surface expression appeared to have higher-than-average ground motions but other strike-slip events contradict this, which believe could be due to ambiguity in identifying coseismic surface rupture in NGA database. Therefore, believe additional study required before Z_{TOR} can be used for strike-slip events. Believe model applicable for $Z_{TOR} = 0$–$15\,\mathrm{km}$.

- Include dip of rupture plane, δ. Believe model applicable for $\delta = 15$–$90°$.

- Assume that τ is approximately equal to standard deviation of inter-event residuals, $\tau_{\ln Y}$, since inter-event terms are not significantly affected by soil nonlinearity. Note that if τ was subject to soil nonlinearity effects it would have only a relatively small effect on σ_T because intra-event σ dominates. σ takes into account soil nonlinearity effects. Assume that $\sigma_{\ln Y}$ and $\sigma_{\ln PGA}$ represent aleatory uncertainty associated with linear site response, reflecting dominance of such records in database.

- Based on statistical tests on binned intra-event residuals conclude that intra-event standard deviations not dependent on V_{S30} once nonlinear site effects are taken into account.

- Use residual analysis to derive trilinear functional form for f_{mag}. Piecewise linear relationship allows greater control of $M > 6.5$ scaling and decouples this scaling from that of small magnitude scaling. Demonstrate using stochastic simulations that trilinear model fits ground motions as well as quadratic model for $M \leq 6.5$. Find that large-magnitude scaling of trilinear model consistent with observed effects of aspect ratio (rupture length divided by rupture width), which was abandoned as explanatory variable when inconsistencies in NGA database for this variable found.

- Original unconstrained regression resulted in prediction of oversaturation at short periods, large magnitudes and short distances. Oversaturation not statistically significant nor is this behaviour scientifically accepted and therefore constrain f_{mag} to saturate at $M > 6.5$ and $R_{RUP} = 0$ when oversaturation predicted by unconstrained regression analysis. Constraint equivalent to setting $c_3 = -c_1 - c_2 - c_5 \ln(c_6)$. Inter- and intra-event residual plots w.r.t. M show predictions relatively unbiased, except for larger magnitudes where saturation constraint leads to overestimation of short-period ground motions.

- Examine inter-event residuals w.r.t. region and find some bias, e.g. find generally positive inter-event residuals at relatively long periods of $M > 6.7$ events in California but only for five events, which believe insufficient to define magnitude scaling for this region. Note that user may wish to take these dependences into account.
- Note that adopted distance-dependence term has computational advantage since it transfers magnitude-dependent attenuation term to outside square root, which significantly improves stability of nonlinear regression. Note that adopted functional form consistent with broadband simulations for 6.5 and 7.5 between 2 and $100\,\mathrm{km}$ and with simple theoretical constraints. Examine intra-event residuals w.r.t. distance and find that they are relatively unbiased.
- Functional form for f_{flt} determined from residual analysis. Find coefficient for normal faulting only marginally significant at short periods but very significant at long periods. Believe long-period effects due to systematic differences in sediment depths rather than source effects, since many normal-faulting events in regions with shallow depths to hard rock (e.g. Italy, Greece and Basin and Range in the USA), but no estimates of sediment depth to correct for this effect. Constrain normal-faulting factor found at short periods to go to zero at long periods based on previous studies.
- Functional form for f_{hng} determined from residual analysis with additional constraints to limit range of applicability so that hanging-wall factor has a smooth transition between hanging and foot walls, even for small Z_{TOR}. Include $f_{hng,M}$, $f_{hng,Z}$ and $f_{hng,\delta}$ to phase out hanging-wall effects at small magnitudes, large rupture depths and large rupture dips, where residuals suggest that effects are either negligible or irresolvable from data. Include hanging-wall effects for normal-faulting and non-vertical strike-slip earthquakes even those statistical evidence is weak but it is consistent with better constrained hanging-wall factor for reverse faults and it is consistent with foam-rubber experiments and simulations.

2.242 Danciu & Tselentis (2007a) & Danciu & Tselentis (2007b)

- Ground-motion model is:

$$\log_{10} Y = a + bM - c\log_{10}\sqrt{R^2 + h^2} + eS + fF$$

  where Y is in $\mathrm{cm/s^2}$, $a = 0.883$, $b = 0.458$, $c = 1.278$, $h = 11.515$, $e = 0.038$, $f = 0.116$, $\tau = 0.109$ (intra-event) and $\sigma = 0.270$ (inter-event).

- Use three site classes:

  B Rock, $V_{s,30} > 800\,\mathrm{m/s}$. $S = 0$. 75 records.

  C Stiff soil, $360 \leq V_s \leq 665\,\mathrm{m/s}$. $S = 1$. 197 records.

  D Soft soil, $200 \leq V_s \leq 360\,\mathrm{m/s}$. $S = 2$. 63 records.

  From initial analysis find that ground-motions on D sites are double those on C sites.

- Use three style-of-faulting categories:

Thrust $F = 1$

Strike-slip $F = 1$

Normal $F = 0$

From initial analysis find that thrust and strike-slip ground motions are similar but greater than normal motions.

- Focal depths between 0 and $30\,\mathrm{km}$ with mean of $10.66\,\mathrm{km}$.
- Most records from earthquakes near the Ionian islands.
- Use records from free-field stations and from basements of buildings with < 2 storeys. Note that some bias may be introduced by records from buildings but due to lack of data from free-field stations these records must be included.
- Use corrected records from ISESD (bandpass filtered 0.25 and $25\,\mathrm{Hz}$).
- Use epicentral distance because most earthquakes are offshore and those that are on-shore do not display evidence of surface faulting and therefore cannot use a fault-based distance measure.
- Data from large events recorded at intermediate and long distances and small events at small distances. Correlation coefficient between magnitude and distance is 0.64.
- Recommend that equation not used outside range of data used.
- Analyse residuals normalized to have zero mean and unity variance (only display results for PGA and SA at $1\,\mathrm{s}$ due to similar results for all periods). Find that residuals do not show trends and are uncorrelated (at more than 99% confidence level) w.r.t. independent variables. Show normality of residuals through histograms for PGA and SA at $1\,\mathrm{s}$.
- Also derive equations for various other strong-motion parameters.

2.243 Douglas (2007)

- Ground-motion model is:

$$\log y = a_1 + a_2 M + a_3 \log \sqrt{(d^2 + 5^2)} + a_{3+i} S_i$$

  Coefficients not reported since purpose is not to develop models for seismic hazard assessments but to derive confidence limits on median PGA and thereafter to examine possible regional dependence of ground motions.

- Rederives models of Joyner & Boore (1981), Boore *et al.* (1993, 1997), Ambraseys *et al.* (1996), Ambraseys *et al.* (2005a), Ulusay *et al.* (2004), Kalkan & Gülkan (2004b) and Sabetta & Pugliese (1987) to find their complete covariance matrices in order to compute confidence limits of the predicted median PGA.
- Uses same site classifications as original studies. $S_i = 1$ for site class i and 0 otherwise.
- Adopts a simple linear functional form and standard one-stage regression method so that the covariance matrices can be easily computed.
- Assumes a fixed coefficient of $5\,\mathrm{km}$ (a rough average value for this coefficient for most models using adopted functional form) inside square root to make function linear.

- Examines 95% confidence limits on PGA since it is standard to use 5% significance levels when testing null hypotheses. Plots predicted median PGAs and their confidence limits for $M_w 5$, 6.5 and 8.0 up to $200\,\mathrm{km}$ to show effects of extrapolation outside range of applicability of models. Finds that confidence limits for models derived using limited data (Ulusay *et al.* , 2004; Kalkan & Gülkan, 2004b; Sabetta & Pugliese, 1987) are wider than models derived using large well-distributed datasets (Joyner & Boore, 1981; Boore *et al.* , 1993, 1997; Ambraseys *et al.* , 1996, 2005a). Notes that for $5.5 < M_w < 7$ and $10 \leq d_f \leq 60\,\mathrm{km}$ the 95%-confidence limits of the median are narrow and within bands 10–30% from the median but for other magnitudes and distances (away from the centroid of data) they are much wider (bands of 100% from the median). Notes that inclusion of data from large magnitude events decreases the width of the confidence limits of the model derived using the data of Boore *et al.* (1993, 1997) compared with that derived using the data of Joyner & Boore (1981) and similarly that derived with the data of Ambraseys *et al.* (2005a) compared with that derived using the data of Ambraseys *et al.* (1996).

2.244 Hong & Goda (2007) & Goda & Hong (2008)

- Ground-motion model is:

$$\ln Y = b_1 + b_2(\mathbf{M} - 7) + b_3(\mathbf{M} - 7)^2 + [b_4 + b_5(\mathbf{M} - 4.5)]\ln[(r_{\mathrm{jb}}^2 + h^2)^{0.5}] + \mathrm{AF}_s$$

  where Y is in g, $b_1 = 1.096$, $b_2 = 0.444$, $b_3 = 0.0$, $b_4 = -1.047$, $b_5 = 0.038$, $h = 5.7$, $\sigma_\eta = 0.190$ (inter-event) and $\sigma_\epsilon = 0.464$ (intra-event) for geometric mean.

- AF_s is the amplification factor due to linear and nonlinear soil behaviour used by Atkinson & Boore (2006), which is a function of $V_{s,30}$ and expected PGA at site with $V_{s,30} = 760\,\mathrm{m/s}$, $\mathrm{PGA}_{\mathrm{ref}}$. Derive equation for $\mathrm{PGA}_{\mathrm{ref}}$ of form $\ln \mathrm{PGA}_{\mathrm{ref}} = b_1 + b_2(M - 7) + b_4 \ln((r_{jb}^2 + h^2)^{0.5})$, where $b_1 = 0.851$, $b_2 = 0.480$, $b_4 = -0.884$ and $h = 6.3\,\mathrm{km}$ for geometric mean (σ not reported).

- Use data from the PEER Next Generation Attenuation (NGA) database.

- Investigate the spatial correlation of ground motions and their variabilities.

- Generate datasets using normally distributed values of M (truncated at ± 2 standard deviations that are reported in the PEER NGA database) for earthquakes and lognormally-distributed values of $V_{s,30}$ (again using standard deviations from PEER NGA database) for stations. Repeat regression analysis and find coefficients very similar to those obtained ignoring the uncertainty in M and $V_{s,30}$.

2.245 Graizer & Kalkan (2007) & Graizer & Kalkan (2008)

- Ground-motion model is:

$$\begin{aligned}\ln(Y) &= \ln(A) - 0.5\ln\left[\left(1-\frac{R}{R_0}\right)^2 + 4D_0^2\frac{R}{R_0}\right] \\ &\quad - 0.5\ln\left[\left(1-\sqrt{\frac{R}{R_1}}\right)^2 + 4D_1^2\sqrt{\frac{R}{R_1}}\right] + b_v\ln\left(\frac{V_{s,30}}{V_A}\right) \\ A &= [c_1\arctan(M+c_2)+c_3]F \\ R_0 &= c_4M+c_5 \\ D_0 &= c_6\cos[c_7(M+c_8)]+c_9\end{aligned}$$

  where Y is in g, $c_1 = 0.14$, $c_2 = -6.25$, $c_3 = 0.37$, $c_4 = 2.237$, $c_5 = -7.542$, $c_6 = -0.125$, $c_7 = 1.19$, $c_8 = -6.15$, $c_9 = 0.525$, $b_v = -0.25$, $V_A = 484.5$, $R_1 = 100\,\mathrm{km}$ and $\sigma = 0.552$.

- Characterise sites by $V_{s,30}$ (average shear-wave velocity in upper $30\,\mathrm{m}$). Note that approximately half the stations have measured shear-wave velocity profiles.

- Include basin effects through modification of D_1. For sediment depth ($Z \geq 1\,\mathrm{km}$ $D_1 = 0.35$; otherwise $D_1 = 0.65$.

- Use three faulting mechanism classes:

Normal 13 records

Strike-slip 1120 records. $F = 1.00$.

Reverse 1450 records. $F = 1.28$ (taken from previous studies).

  but only retain two (strike-slip and reverse) by combining normal and strike-slip categories.

- Only use earthquakes with focal depths $< 20\,\mathrm{km}$. Focal depths between 4.6 and $19\,\mathrm{km}$.

- Exclude data from aftershocks.

- Use data from: Alaska (24 records), Armenia (1 record), California (2034 records), Georgia (8), Iran (7 records) Italy (10 records), Nevada (8 records), Taiwan (427 records), Turkey (63 records) and Uzbekistan (1 record).

- Most data from $5.5 \leq M_w \leq 7.5$.

- Adopt functional form to model: a constant level of ground motion close to fault, a slope of about R^{-1} for $> 10\,\mathrm{km}$ and $R^{-1.5}$ at greater distances ($> 100\,\mathrm{km}$) and observation (and theoretical results) that highest amplitude ground motions do not always occur nearest the fault but at distances of 3–$10\,\mathrm{km}$.

- Choose functional form based on transfer function of a SDOF oscillator since this has similar characteristics to those desired.

- Note that magnitude scaling may need adjusting for small magnitudes.

- Firstly regress for magnitude and distance dependency and then regress for site and basin effects.
- Examine residual w.r.t. magnitude and distance and observe no significant trends.
- Compare predictions to observations for 12 well-recorded events in the dataset and find that the observations are well predicted for near and far distances.
- Demonstrate (for the 2004 Parkfield earthquake) that it is possible to add an additional 'filter' term in order to predict ground motions at large distances without modifying the other terms.

2.246 Massa *et al.* (2007)

- Ground-motion model is:

$$\log_{10}(Y) = a + bM_L + c\log(R) + dS_{\mathrm{soil}}$$

  where Y is in g, $a = -3.2191 \pm 0.16$, $b = 0.7194 \pm 0.025$, $c = -1.7521 \pm 0.075$, $d = 0.1780$ and $\sigma = 0.282$.

- Originally use three site classes based on Eurocode 8:

  A Rock, $V_{s,30} > 800\,\mathrm{m/s}$. Marine clay or other rocks (Lower Pleistocene and Pliocene), volcanic rock and deposits. 11 stations. 833 records.

  B Stiff soil, $360 < V_{s,30} < 800\,\mathrm{m/s}$. Colluvial, alluvial, lacustrine, beach, fluvial terraces, glacial deposits and clay (Middle-Upper Pleistocene). Sand and loose conglomerate (Pleistocene and Pliocene). Travertine (Pleistocene and Holocene). 6 stations. 163 records.

  C Soft soil, $V_{s,30} < 360\,\mathrm{m/s}$. Colluvial, alluvial, lacustrine, beach and fluvial terrace deposits (Holocene). 3 stations. 67 records.

  Classify stations using geological maps. Find that results obtained using this classification are not realistic because of some stations on very thick ($> 1000\,\mathrm{m}$) sedimentary deposits whose amplification factors are small. Therefore, use two site classes using H/V ratios both using noise and earthquake records. Confirm H/V results by computing magnitude residuals at each station.

  Final site classes are:

  Rock Site amplification factors < 2 at all considered frequencies from H/V analysis. 422 records. $S_{\mathrm{soil}} = 0$.

  Soil Site amplification factors > 2. 641 records. $S_{\mathrm{soil}} = 1$.

- Use data from velocimeters (31 stations) and accelerometers (2 stations) from 33 sites with sampling rates of $62.5\,\mathrm{samples/s}$.
- Relocate events and calculate M_L.
- Exclude data from $M_L < 2.5$ and $r_{hypo} > 300\,\mathrm{km}$.
- Few near-source records ($r_{hypo} < 150\,\mathrm{km}$) from $M_L > 4$ but for $M_L < 4$ distances from 0 to $300\,\mathrm{km}$ well represented.

- Exclude records with signal-to-noise ratios $< 10\,\mathrm{dB}$.
- Correct for instrument response and bandpass filter between 0.5 and $25\,\mathrm{Hz}$ and then the velocimetric records have been differentiated to obtain acceleration.
- Visually inspect records to check for saturated signals and noisy records.
- Compare records from co-located velocimetric and accelerometric instruments and find that they are very similar.
- Compare PGAs using larger horizontal component, geometric mean of the two horizontal components and the resolved component. Find that results are similar and that the records are not affected by bias due to orientation of sensors installed in field.
- Try including a quadratic magnitude term but find that it does not reduce uncertainties and therefore remove it.
- Try including an anelastic attenuation term but find that the coefficient is not statistically significant and that the coefficient is positive and close to zero and therefore remove this term.
- Try using a term $c \log_{10} \sqrt{R_{\mathrm{epi}}^2 + h^2}$ rather than $c \log_{10}(R)$ but find that h is not well constrained and hence PGAs for distances $< 50\,\mathrm{km}$ underpredicted.
- Find that using a maximum-likelihood regression technique leads to very similar results to the one-stage least-squares technique adopted, which relate to lack of correlation between magnitudes and distances in dataset.
- Find site coefficients via regression following the derivation of a, b and c using the 422 rock records.
- Compare observed and predicted ground motions for events in narrow (usually 0.3 units) magnitude bands. Find good match.
- Examine residuals w.r.t. magnitude and distance and find no significant trends except for slight underestimation for short distances and large magnitudes. Also check residuals for different magnitude ranges. Check for bias due to non-triggering stations.
- Compare predicted PGAs to observations for 69 records from central northern Italy from magnitudes 5.0–6.3 and find good match except for $r_{hypo} < 10\,\mathrm{km}$ where ground motions overpredicted, which relate to lack of near-source data.

2.247 Popescu *et al.* (2007)

- Ground-motion model is:

$$\log A = C_1 M_w + C_2 \log R + C_3$$

  where A in in $\mathrm{cm/s^2}$, $C_1 = 0.80 \pm 0.05$, $C_2 = -0.30 \pm 0.08$, $C_3 = -2.93$ and $\sigma = 0.314$ using r_{epi} and $C_1 = 0.79 \pm 0.05$, $C_2 = -0.89 \pm 0.38$, $C_3 = -1.43$ and $\sigma = 0.341$ using r_{hypo}.
- Adjust observations by multiplicative factor S to account for site conditions ($0.8 \le S \le 1$ for hard rocks, $0.7 \le S \le 0.8$ for thin sedimentary layers and $0.65 \le S \le 0.7$ for thick sedimentary cover.

- Focal depths between 60 and $166\,\mathrm{km}$.
- Data from digital strong-motion network (K2 instruments) from 1997 to 2000 ($4 \le M_w \le 6$) plus data (SMA-1) from 30th August 1986 ($M_w 7.1$) and 30th and 31st May 1990 ($M_w 6.9$ and 6.4) earthquakes.
- Regression in two steps: a) dependence on M_w found and then b) dependence on R is found (details on this procedure are not given).
- Also regress using just K2 data ($\log A = 0.94 \pm 0.09 M_w - 1.01 \pm 0.42 \log R - 1.84$, $\sigma = 0.343$) and using r_{epi} ($\log A = 0.89 \pm 0.09 M_w - 0.28 \pm 0.09 \log \Delta - 3.35$, $\sigma = 0.322$). Note that correlation coefficients are higher and σs are lower when all data is used and that match (based on relative residuals) to data from 1986 and 1990 earthquakes is better when all data is used.
- Present relative residuals for sites in epicentral area and in Bucharest. Note that for 63% of earthquakes relative errors are $< 50\%$ for at least one station; for 43% of earthquake relative errors are $< 30\%$ for at least one station; and for 9 earthquakes relative errors are smaller than 10% for at least one station (BMG, the extreme site). Based on this analysis it is concluded that predictions more reliable in far-field than in epicentral area. Also find that largest absolute residuals are for MLR (stiff rock).
- Note largest relative errors are for $4 \le M_w \le 4.5$.

2.248 Sobhaninejad *et al.* (2007)

- Ground-motion model is:

  $$\log y = a_1 + a_2 M_w + (a_3 + a_4 Mw) \log \sqrt{r_{jb}^2 + a_5^2} + a_6 S_S + a_7 S_A + a_8 F_N + a_9 F_T + a_{10} F_O$$

  where y is in $\mathrm{m/s^2}$, $a_1 = -0.703$, $a_2 = 0.392$, $a_3 = -0.598$, $a_4 = -0.100$, $a_5 = -7.063$, $a_6 = 0.186$, $a_7 = 0.125$, $a_8 = 0.082$, $a_9 = 0.012$ and $a_{10} = -0.038$ (do not report σ but unbiased mean square error) for horizontal PGA; and $a_1 = 0.495$, $a_2 = 0.027$, $a_3 = -2.83$, $a_4 = 0.235$, $a_5 = 7.181$, $a_6 = 1.150$, $a_7 = 1.103$, $a_8 = -0.074$, $a_9 = 0.065$ and $a_{10} = -0.170$ (do not report σ but unbiased mean square error).

- Use three site categories:

Soft soil $S_S = 1$, $S_A = 0$.

Stiff soil $S_A = 1$, $S_S = 0$.

Rock $S_S = 0$, $S_A = 0$.

- Use four faulting mechanisms:

Normal $F_N = 1$, $F_T = 0$, $F_O = 0$.

Strike-slip $F_N = 0$, $F_T = 0$, $F_O = 0$.

Thrust $F_T = 1$, $F_N = 0$, $F_O = 0$.

Odd $F_O = 1$, $F_N = 0$, $F_T = 0$.

- Use same data and functional form as Ambraseys *et al.* (2005a) and Ambraseys *et al.* (2005b) but exclude six records that were not available.

- Use genetic (global optimization) algorithm to find coefficients so as to find the global (rather than a local) minimum. Use the unbiased mean square error as the error (cost or fitness) function in the algorithm. Use 20 chromosomes as initial population, best-fitness selection for offspring generation, uniform random selection for mutation of chromosomes and heuristic crossover algorithm for generation of new offspring.
- Find smaller (by 26% for horizontal and 16.66% for vertical) unbiased mean square error than using standard regression techniques.

2.249 Tavakoli & Pezeshk (2007)

- Ground-motion model is:

$$\log_{10} y = \theta_1 + \theta_2 M + \theta_3 M^2 + \theta_4 R + \theta_5 \log_{10}(R + \theta_6 10^{\theta_7 M})$$

  where y is in $\mathrm{cm/s^2}$, $\theta_1 = -3.4712$, $\theta_2 = 2.2639$, $\theta_3 = -0.1546$, $\theta_4 = 0.0021$, $\theta_5 = -1.8011$, $\theta_6 = 0.0490$, $\theta_7 = 0.2295$, $\sigma_r = 0.2203$ (intra-event) and $\sigma_e = 0.2028$ (inter-event).

- All records from rock sites.
- Strong correlation between magnitude and distance in dataset.
- Use a derivative-free approach based on a hybrid genetic algorithm to derive the model. Use a simplex search algorithm to reduce the search domain to improve convergence speed. Then use a genetic algorithm to obtain the coefficients and uncertainties using one-stage maximum-likelihood estimation. Believe that approach is able to overcome shortcomings of previous methods in providing reliable and stable solutions although it is slower.
- In hybrid genetic algorithm an initial population of possible solutions is constructed in a random way and represented as vectors called strings or chromosomes of length determined by number of regression coefficients and variance components. Population size is usually more than twice string length. Each value of population array is encoded as binary string with known number of bits assigned according to level of accuracy or range of each variable. Use three operations (reproduction/selection, crossover and mutation) to conduct directed search. In reproduction phase each string assigned a fitness value derived from its raw performance measure given by objective function. Probabilities of choosing a string is related to its fitness value. Crossover or mating combines pairs of strings to create improved strings in next population. In mutation one or more bits of every string are altered randomly. The process is then repeated until a termination criterion is met. Demonstrate approach using test function and find small maximum bias in results. Conclude that method is reliable.
- Use Taiwanese dataset of Chen & Tsai (2002) to demonstrate method.
- Compare results with those obtained using methods of Brillinger & Preisler (1985), Joyner & Boore (1993) and Chen & Tsai (2002). Find differences in coefficients (although predictions are very similar except at edges of dataspace) and standard deviations (slightly lower for proposed method).
- Compare predicted motions for $M_L 5.5$ with observations for $M_L 5$–6. Find good fit.

- Plot total residuals against magnitude and distance and find no trends.

- Note that residuals show that model is satisfactory up to $100\,\mathrm{km}$ but for larger distances assumption of geometric spreading of body waves in not appropriate due to presence of waves reflected off Moho.

- Note that near-source saturation should be included. Apply proposed method using a complex functional form with different equations for three distance ranges and compare results to those using simple functional form. Find differences at short and large distances.

2.250 Tejeda-Jácome & Chávez-García (2007)

- Ground-motion model is:

$$\ln A = c_1 + c_2 M - c_3 \ln h - c_4 \ln R$$

  where A is in $\mathrm{cm/s^2}$, $c_1 = -0.5342$, $c_2 = 2.1380$, $c_3 = 0.4440$, $c_4 = 1.4821$ and $\sigma = 0.28$ for horizontal PGA and $c_1 = -0.5231$, $c_2 = 1.9876$, $c_3 = 0.5502$, $c_4 = 1.4038$ and $\sigma = 0.27$ for vertical PGA.

- Most stations on rock or firm ground. 4 instruments (from close to coast) installed on sandy or silty-sandy soils. Not enough data to correct for site effects or derive site coefficients. Check residuals (not shown) for each station and find no systematic bias.

- Focal depths h between 3.4 and $76.0\,\mathrm{km}$ (most $< 40\,\mathrm{km}$). No correlation between h and r_{epi}.

- Use data from 12 (5 Etnas and 7 GSR-18s) temporary and 5 permanent strong-motion stations.

- Since data from digital instruments only apply baseline correction.

- Exclude data from 3 events only recorded at 3 stations.

- Relocate earthquakes because of poor locations given by agencies. Recompute M_L from accelerograms.

- Inclusion of h leads to less scatter but note need for larger database to better understand effect of h.

- Examine residuals w.r.t. distance and find no trend or bias.

2.251 Abrahamson & Silva (2008) & Abrahamson & Silva (2009)

- Ground-motion model is:

$$
\begin{aligned}
\ln \mathrm{Sa(g)} &= f_1(M, R_{rup}) + a_{12}F_{RV} + a_{13}F_{NM} + a_{15}F_{AS} + f_5(\widehat{\mathrm{PGA}_{1100}}, V_{S30}) \\
&\quad + F_{HW} f_4(R_{jb}, R_{rup}, R_x, W, \delta, Z_{TOR}, M) + f_6(Z_{TOR}) + f_8(R_{rup}, M) \\
&\quad + f_{10}(Z_{1.0}, V_{S30}) \\
f_1(M, R_{rup}) &= \begin{cases} a_1 + a_4(M - c_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - c_1)]\ln(R) & \text{for } M \le c_1 \\ a_1 + a_5(M - c_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - c_1)]\ln(R) & \text{for } M > c_1 \end{cases} \\
R &= \sqrt{R_{rup}^2 + c_4^2} \\
f_5(\widehat{\mathrm{PGA}_{1100}}, V_{S30}) &= \begin{cases} a_{10}\ln\left(\frac{V_{S30}^*}{V_{LIN}}\right) - b\ln(\widehat{\mathrm{PGA}_{1100}} + c) & \\ +b\ln\left(\widehat{\mathrm{PGA}_{1100}} + c\left(\frac{V_{S30}^*}{V_{LIN}}\right)^n\right) & \text{for } V_{S30} < V_{LIN} \\ (a_{10} + bn)\ln\left(\frac{V_{S30}^*}{V_{LIN}}\right) & \text{for } V_{S30} \ge V_{LIN} \end{cases} \\
\text{where } V_{S30}^* &= \begin{cases} V_{S30} & \text{for } V_{S30} < V_1 \\ V_1 & \text{for } V_{S30} \ge V_1 \end{cases} \\
\text{and } V_1 &= \begin{cases} 1500 & \text{for } T \le 0.50\,\mathrm{s} \\ \exp[8.0 - 0.795\ln(T/0.21)] & \text{for } 0.50 < T \le 1\,\mathrm{s} \\ \exp[6.76 - 0.297\ln(T)] & \text{for } 1 < T < 2\,\mathrm{s} \\ 700 & \text{for } T \ge 2\,\mathrm{s} \end{cases} \\
f_4(R_{jb}, R_{rup}, \delta, Z_{TOR}, M, W) &= a_{14}T_1(R_{jb})T_2(R_x, W, \delta)T_3(R_x, Z_{TOR})T_4(M)T_5(\delta) \\
\text{where } T_1(R_{jb}) &= \begin{cases} 1 - \frac{R_{jb}}{30} & \text{for } R_{jb} < 30\,\mathrm{km} \\ 0 & \text{for } R_{jb} \ge 30\,\mathrm{km} \end{cases} \\
T_2(R_x, W, \delta) &= \begin{cases} 0.5 + \frac{R_x}{2W\cos(\delta)} & \text{for } R_x \le W\cos(\delta) \\ 1 & \text{for } R_x > W\cos(\delta) \text{ or } \delta = 90^\circ \end{cases} \\
T_3(R_x, Z_{TOR}) &= \begin{cases} 1 & \text{for } R_x \ge Z_{TOR} \\ \frac{R_x}{Z_{TOR}} & \text{for } R_x < Z_{TOR} \end{cases} \\
T_4(M) &= \begin{cases} 0 & \text{for } M \le 6 \\ M - 6 & \text{for } 6 < M < 7 \\ 1 & \text{for } M \ge 7 \end{cases} \\
T_5(\delta) &= \begin{cases} 1 - \frac{\delta - 30}{60} & \text{for } \delta \ge 30 \\ 1 & \text{for } \delta < 30 \end{cases} \\
f_6(Z_{TOR}) &= \begin{cases} \frac{a_{16}Z_{TOR}}{10} & \text{for } Z_{TOR} < 10\,\mathrm{km} \\ a_{16} & \text{for } Z_{TOR} \ge 10\,\mathrm{km} \end{cases} \\
f_8(R_{rup}, M) &= \begin{cases} 0 & \text{for } R_{rup} < 100\,\mathrm{km} \\ a_{18}(R_{rup} - 100)T_6(M) & \text{for } R_{rup} \ge 100\,\mathrm{km} \end{cases} \\
\text{where } T_6(M) &= \begin{cases} 1 & \text{for } M < 5.5 \\ 0.5(6.5 - M) + 0.5 & \text{for } 5.5 \le M \le 6.5 \\ 0.5 & \text{for } M > 6.5 \end{cases} \\
f_{10}(Z_{1.0}, V_{S30}) &= a_{21}\ln\left(\frac{Z_{1.0} + c_2}{\hat{Z}_{1.0}(V_{S30}) + c_2}\right) + \begin{cases} a_{22}\ln\left(\frac{Z_{1.0}}{200}\right) & \text{for } Z_{1.0} \ge 200 \\ 0 & \text{for } Z_{1.0} < 200 \end{cases} \\
\text{where } \ln[\hat{Z}_{1.0}(V_{S30})] &= \begin{cases} 6.745 & \text{for } V_{S30} < 180\,\mathrm{m/s} \\ 6.745 - 1.35\ln\left(\frac{V_{S30}}{180}\right) & \text{for } 180 \le V_{S30} \le 500\,\mathrm{m/s} \\ 5.394 - 4.48\ln\left(\frac{V_{S30}}{500}\right) & \text{for } V_{S30} > 500\,\mathrm{m/s} \end{cases} \\
a_{21} &= \begin{cases} 0 & \text{for } V_{S30} \ge 1000 \\ \dfrac{-(a_{10}+bn)\ln\left(\frac{V_{S30}^*}{\min(V_1,1000)}\right)}{\ln\left(\frac{Z_{1.0}+c_2}{\hat{Z}_{1.0}+c_2}\right)} & \text{for } (a_{10}+bn)\ln\left(\frac{V_{S30}^*}{\min(V_1,1000)}\right) + e_2\ln\left(\frac{Z_{1.0}+c_2}{\hat{Z}_{1.0}+c_2}\right) < 0 \\ e_2 & \text{otherwise} \end{cases} \\
e_2 &= \begin{cases} 0 & \text{for } T < 0.35\,\mathrm{s} \text{ or } V_{S30} > 1000 \\ -0.25\ln\left(\frac{V_{S30}}{1000}\right)\ln\left(\frac{T}{0.35}\right) & \text{for } 0.35 \le T \le 2\,\mathrm{s} \\ -0.25\ln\left(\frac{V_{S30}}{1000}\right)\ln\left(\frac{2}{0.35}\right) & \text{for } T > 2\,\mathrm{s} \end{cases} \\
a_{22} &= \begin{cases} 0 & \text{for } T < 2\,\mathrm{s} \\ 0.0625(T - 2) & \text{for } T \ge 2\,\mathrm{s} \end{cases}
\end{aligned}
$$

The model for the standard deviation is:

$$\sigma_B(M,T) = \sqrt{\sigma_0^2(M,T)-\sigma_{Amp}^2(T)}$$

$$\sigma(T,M,\widehat{\mathrm{PGA}_{1100}},V_{S30}) = \left[\begin{array}{l}\sigma_B^2(M,T)+\sigma_{Amp}^2(T)\\ +\left(\frac{\partial \ln \mathrm{Amp}(T,\widehat{\mathrm{PGA}_{1100}},V_{S30})}{\partial \ln \mathrm{PGA}_{1100}}\right)^2\sigma_B^2(M,\mathrm{PGA})\\ +2\left(\frac{\partial \ln \mathrm{Amp}(T,\widehat{\mathrm{PGA}_{1100}},V_{S30})}{\partial \ln \mathrm{PGA}_{1100}}\right)\\ \times\sigma_B(M,T)\sigma_B(M,\mathrm{PGA})\rho_{\epsilon/\sigma}(T,\mathrm{PGA})\end{array}\right]^{1/2}$$

$$\frac{\partial \ln \mathrm{Amp}(T,\widehat{\mathrm{PGA}_{1100}},V_{S30})}{\partial \ln \mathrm{PGA}_{1100}} = \begin{cases} 0 & \text{for } V_{S30}\geq V_{LIN}\\ \frac{-b(T)\widehat{\mathrm{PGA}_{1100}}}{\widehat{\mathrm{PGA}_{1100}}+c}+\frac{-b(T)\widehat{\mathrm{PGA}_{1100}}}{\widehat{\mathrm{PGA}_{1100}}+c\left(\frac{V_{S30}}{V_{LIN}}\right)^n} & \text{for } V_{S30}<V_{LIN}\end{cases}$$

$$\sigma_0(M) = \begin{cases} s_1 & \text{for } M<5\\ s_1+\left(\frac{s_2-s_1}{2}\right)(M-5) & \text{for } 5\leq M\leq 7\\ s_2 & \text{for } M>7\end{cases}$$

$$\tau_0(M) = \begin{cases} s_3 & \text{for } M<5\\ s_3+\left(\frac{s_4-s_3}{2}\right)(M-5) & \text{for } 5\leq M\leq 7\\ s_4 & \text{for } M>7\end{cases}$$

where Sa is in g, $\mathrm{PG\hat{A}}_{1100}$ is median peak acceleration for $V_{S30}=1100\,\mathrm{m/s}$, σ_B and τ_B ($=\tau_0(M,T)$) are intra-event and inter-event standard deviations, σ_0 and τ_0 are intra-event and inter-event standard deviations of the observed ground motions for low levels of outcrop rock motions (directly from regression), σ_{amp} is intra-event variability of the site amplification factors (assumed equal to 0.3 for all periods based on 1D site response results), $c_1=6.75$, $c_4=4.5$, $a_3=0.265$, $a_4=-0.231$, $a_5=-0.398$, $N=1.18$, $c=1.88$, $c_2=50$, $V_{LIN}=865.1$, $b=-1.186$, $a_1=0.804$, $a_2=-0.9679$, $a_8=-0.0372$,$a_{10}=0.9445$, $a_{12}=0.0000$, $a_{13}=-0.0600$, $a_{14}=1.0800$, $a_{15}=-0.3500$, $a_{16}=0.9000$, $a_{18}=-0.0067$, $s_1=0.590$ and $s_2=0.470$ for V_{S30} estimated, $s_1=0.576$ and $s_2=0.453$ for V_{S30} measured, $s_3=0.470$, $s_4=0.300$ and $\rho(T,\mathrm{PGA})=1.000$.

- Characterise sites using V_{S30} and depth to engineering rock ($V_s=1000\,\mathrm{m/s}$), $Z_{1.0}$. Prefer $V_{s,30}$ to generic soil/rock categories because it is consistent with site classification in current building codes. Note that this does not imply that $30\,\mathrm{m}$ is key depth range for site response but rather that $V_{s,30}$ is correlated with entire soil profile.
- Classify events in three fault mechanism categories:

$F_{RV}=1$, $F_{NM}=0$ Reverse, reverse/oblique. Earthquakes defined by rake angles between 30 and $150°$.

$F_{RV}=0$, $F_{NM}=1$ Normal. Earthquakes defined by rake angles between -60 and $-120°$.

$F_{RV}=0$, $F_{NM}=0$ Strike-slip. All other earthquakes.

- Believe that model applicable for $5\leq M_w\leq 8.5$ (strike-slip) and $5\leq M_w\leq 8.0$ (dip-slip) and $0\leq d_r\leq 200\,\mathrm{km}$.
- Use simulations for hard-rock from 1D finite-fault kinematic source models for $6.5\leq M_w\leq 8.25$, 3D basin response simulations for sites in southern California and equivalent-linear site response simulations to constrain extrapolations beyond the limits of the empirical data.
- Select data from the Next Generation Attenuation (NGA) database (flat-file version 7.2). Include data from all earthquakes, including aftershocks, from shallow crustal earthquakes in active tectonic regions under assumption that median ground motions from

shallow crustal earthquakes at $d_r < 100\,\mathrm{km}$ are similar. This assumes that median stress-drops are similar between shallow crustal events in: California, Alaska, Taiwan, Japan, Turkey, Italy, Greece, New Zealand and NW China. Test assumption by comparing inter-event residuals from different regions to those from events in California. Since aim is for model for California and since difference in crustal structure and attenuation can affect ground motions at long distances exclude data from $d_r > 100\,\mathrm{km}$ from outside western USA.

- Also exclude these data: events not representative of shallow crustal tectonics, events missing key source metadata, records not representative of free-field motion, records without a $V_{s,30}$ estimate, duplicate records from co-located stations, records with missing horizontal components or poor quality accelerograms and records from western USA from $d_r > 200\,\mathrm{km}$.
- Classify earthquakes by event class: AS (aftershock) ($F_{AS} = 1$); MS (mainshock), FS (foreshock) and swarm ($F_{AS} = 0$). Note that classifications not all unambiguous.
- Use depth-to-top of rupture, Z_{TOR}, fault dip in degrees, δ and down-dip rupture width, W.
- Use r_{jb} and R_x (horizontal distance from top edge of rupture measured perpendicular to fault strike) to model hanging wall effects. For hanging wall sites, defined by vertical projection of the top of the rupture, $F_{HW} = 1$. T_1, T_2 and T_3 constrained by 1D rock simulations and the Chi-Chi data. T_4 and T_5 constrained by well-recorded hanging wall events. Only a_{14} was estimated by regression. State that hanging-wall scaling is one of the more poorly-constrained parts of model[14].
- Records well distributed w.r.t. M_w and r_{rup}.
- For four Chi-Chi events show steep distance decay than other earthquakes so include a separate coefficient for the $\ln(R)$ term for these events so they do not have a large impact on the distance scaling. Retain these events since important for constraining other aspects of the model, e.g. site response and intra-event variability.
- Only used records from $5 \leq M \leq 6$ to derive depth-to-top of rupture (Z_{TOR}) dependence to limit the effect on the relation of the positive correlation between Z_{TOR} and M.
- Constrain (outside the main regression) the large distance ($R_{rup} > 100\,\mathrm{km}$) attenuation for small and moderate earthquakes ($4 \leq M \leq 5$) using broadband records of 3 small ($M4$) Californian earthquakes because limited data for this magnitude-distance range in NGA data set.
- Note difficult in developing model for distinguishing between shallow and deep soil sites due to significant inconsistencies between V_{S30} and depth of soil ($Z_{1.0}$), which believe to be unreliable in NGA Flat-File. Therefore, develop soil-depth dependence based on 1D (for $Z_{1.0} < 200\,\mathrm{m}$) and 3D (for $Z_{1.0} > 200\,\mathrm{m}$) site response simulations. Motion for shallow soil sites do not fall below motion for $V_{S30} = 1000\,\mathrm{m/s}$.

[14] Model for T_5 reported here is that given in 2009 errata. In original reference: $T_5 = 1 - (\delta - 70)/20$ for $\delta \geq 70$ and 1 otherwise).

- T_D denotes period at which rock ($V_{S30} = 1100\,\mathrm{m/s}$) spectrum reaches constant displacement. Using point-source stochastic model and 1D rock simulations evaluate magnitude dependence of T_D as $\log_{10}(T_D) = -1.25 + 0.3M$. For $T > T_D$ compute rock spectral acceleration at T_D and then scale this acceleration at T_D by $(T_D/T)^2$ for constant spectral displacements. The site response and soil depth scaling is applied to this rock spectral acceleration, i.e. $\mathrm{Sa}(T_D, V_{S30} = 1100)\frac{T_D^2}{T^2} + f_5(\mathrm{PG\hat{A}}_{1100}, V_{S30}, T) + f_{10}(Z_{1.0}, V_{S30}, T)$.
- Reduce standard deviations to account for contribution of uncertainty in independent parameters M, R_{rup}, Z_{TOR} and V_{S30}.
- Note that regression method used prevents well-recorded earthquakes from dominating regression.
- Examine inter-event residuals and find that there is no systemic trend in residuals for different regions. Find that residuals for $M > 7.5$ are biased to negative values because of full-saturation constraint. Examine intra-event residuals and find no significant trend in residuals.
- Although derive hanging-wall factor only from reverse-faulting data suggest that it is applied to normal-faulting events as well.
- State that should use median PGA_{1100} for nonlinear site amplification even if conducting a seismic hazard analysis for above median ground motions.
- State that if using standard deviations for estimated V_{S30} and V_{S30} is accurate to within 30% do not need to use a range of V_{S30} but if using measured-V_{S30} standard deviations then uncertainty in measurement of V_{S30} should be estimated by using a range of V_{S30} values.
- State that if do not know $Z_{1.0}$ then use median $Z_{1.0}$ estimated from equations given and do not adjust standard deviation.

2.252 Ágústsson *et al.* (2008)

- Ground-motion models are:

$$\log_{10}(\mathrm{acceleration}) = a\log_{10}(R) + b\log_{10}(M) + c$$

  where acceleration is in $\mathrm{m/s^2}$, $a = -1.95600$, $b = 9.59878$, $c = -4.87778$ and $\sigma = 0.4591$, and:

$$\log_{10}(\mathrm{acceleration}) = a\log_{10}(R) + bM + c$$

  where $a = -1.96297$, $b = 0.89343$, $c = -2.65660$ and $\sigma = 0.4596$.

- Select data from SIL database with $M_{Lw} > 3.5$ in latitude range 63.5 to 64.3°N and longitude range 18 to 23.5°W between July 1992 and April 2007.
- Exclude data where several earthquakes are superimposed and retain only 'clean' waveforms.
- Most data from $5\,\mathrm{Hz}$ Lennarz seismometers. Some from $1\,\mathrm{Hz}$ and long-period instruments. Sampling frequency is $100\,\mathrm{Hz}$.

- Use data from SW Iceland plus data from Reykjanes Ridge and Myrdalsjokull volcano.
- Investigate decay in several individual earthquakes and fit equations of form $\log y = a \log R + b$. Note that relations are well behaved so fit entire dataset.

2.253 Aghabarati & Tehranizadeh (2008)

- Ground-motion model is:

$$
\begin{aligned}
\ln y &= c_1 + f_1(M_w) + f_2(M_w)f_3(R) + f_4(F) + \mathrm{FR}f_5(Z_{FR}) + \\
&\quad \mathrm{FS}f_6(Z_{FR}) + f_7(\mathrm{HW}, R_{JB}, M_w, \mathrm{DIP}) + \\
&\quad f_8(V_{s,30}, V_{lin}, \mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) + f_9(V_{s,30}, Z_{1.5}) \\
\text{where for } & M_w \leq c_0 \\
f_1(M_w) &= c_3(M_w - c_0) + c_8(T)(8.5 - M_w)^n \\
f_2(M_w) &= c_2(T) + c_4(M_w - c_0) \\
\text{and for } & M_w > c_0 \\
f_1(M_w) &= c_5(M_w - c_0) + c_8(T)(8.5 - M_w)^n \\
f_2(M_w) &= c_2(T) + c_6(M_w - c_0) \\
f_3(R) &= \ln\sqrt{R_{rup}^2 + c_7(T)^2} \\
f_4(F) &= c_9(T)\mathrm{FR} + c_{10}(T)\mathrm{FS} + c_{11}(T)\mathrm{FN} \\
f_5(Z_{\mathrm{FR}}) &= \begin{cases} 0 & Z_{top} \leq 2\,\mathrm{km} \\ c_{12}(T)(Z_{top} - 2)/3 & 2 < Z_{top} \leq 5\,\mathrm{km} \\ c_{12}(T) & 5 < Z_{top} \leq 10\,\mathrm{km} \\ c_{12}(T)[1 - (Z_{top} - 10)/5] & 5 < Z_{top} \leq 10\,\mathrm{km}(sic) \\ 0 & Z_{top} > 10\,\mathrm{km} \end{cases} \\
f_6(Z_{\mathrm{FS}}) &= \begin{cases} c_{13}(T)Z_{top}/2 & 0 < Z_{top} \leq 2\,\mathrm{km} \\ c_{13}(T) & 2 < Z_{top} \leq 4\,\mathrm{km} \\ c_{13}(T)[1 - (Z_{top} - 4)/2] & 4 < Z_{top} \leq 6\,\mathrm{km} \\ 0 & Z_{top} > 6\,\mathrm{km} \end{cases} \\
g_1(R_{JB}) &= \begin{cases} 1 - R_{JB}/45 & 0 \leq R_{JB} < 15\,\mathrm{km} \\ \frac{2}{3}(2 - R_{JB}/15) & 15 \leq R_{JB} < 30\,\mathrm{km} \\ 0 & R_{JB} \geq 30\,\mathrm{km} \end{cases} \\
g_2(M_w) &= \begin{cases} 0 & M_w < 6.0 \\ 2(M_w - 6) & 6.0 \leq M_w < 6.5 \\ 1 & M_w \geq 6.5 \end{cases} \\
g_3(\mathrm{DIP}) &= \begin{cases} 1 - (\mathrm{DIP} - 70)/20 & \mathrm{DIP} \geq 70 \\ 1 & \mathrm{DIP} < 70 \end{cases} \\
f_7(\mathrm{HW}, R_{JB}, M_w, \mathrm{DIP}) &= c_{14}(T)\mathrm{HW}g_1(R_{JB})g_2(M_w)g_3(\mathrm{DIP}) \\
f_8(V_{s,30}, V_{lin}, \mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) &= g_4(V_{s,30}, V_{lin}) + g_5(\mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) \\
g_4(V_{s,30}, V_{lin}) &= c_{15}(T)\ln(V_{s,30}/V_{lin}) \\
g_5(\mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) &= \begin{cases} c_{16}(T)\ln(\mathrm{PGA}_{min}/0.1) & \mathrm{PGA}_{non-lin} < a_1 \\ c_{16}(T)[\ln(\mathrm{PGA}_{min}/0.1) & \\ +a\ln(\mathrm{PGA}_{non-lin}/a_1) & \\ +b(\ln(\mathrm{PGA}_{non-lin}/a_1))^2] & a_1 \leq \mathrm{PGA}_{non-lin} \leq a_2 \\ c_{16}(T)\ln(\mathrm{PGA}_{non-lin}/0.1) & \mathrm{PGA}_{non-lin} \geq a_2 \end{cases} \\
f_9(V_{s,30}, Z_{1.5}) &= g_6(V_{s,30}, Z_{1.5}, \hat{Z}) + g_7(Z_D, Z_{1.5}) \\
g_6(V_{s,30}, Z_{1.5}, \hat{Z}) &= c_{17}(T)(1/\hat{Z})\ln(V_{s,30}/1500)\ln(Z_{1.5}) \\
g_7(Z_{1.5}, Z_D) &= Z_D c_{18}(T)K_1(1 - \exp(-(Z_{1.5} - 200)/300)) + \\
&\quad Z_D c_{19}(T)K_2(1 - \exp(-(Z_{1.5} - 200)/4000))
\end{aligned}
$$

where y is in g, $c_1 = 1.81$, $c_2 = -1.18$, $c_7 = 8.647$, $c_8 = -0.028$, $c_9 = -0.176$, $c_{10} = -0.266$, $c_{11} = -0.476$, $c_{12} = 0.52$, $c_{13} = -0.32$, $c_{14} = 0.4$, $c_{15} = -0.36$, $c_{17} = 0$, $c_{18} = 0$, $c_{19} = 0$, $c_{20} = 0.496$, $c_{21} = 0.427$, $K_1 = 2.260$, $K_2 = 1.04$, $V_{lin} = 760$, $\sigma = c_{20}(T) + [c_{21}(T) - c_{20}(T)]M_w$ for $5.0 \leq M_w < 7.0$ and $\sigma = c_{21}(T)$ for $M_w \geq 7.0$.

- Use $V_{s,30}$ to characterize site conditions.
- Characterize basin by depth to $V_s = 1500\,\mathrm{m/s}$, $Z_{1.5}$, since more likely to be obtained for engineering projects.
- Use three mechanism classes:
  1. Normal. 34 records. $\mathrm{FN} = 1$, $\mathrm{FS} = \mathrm{FR} = 0$.
  2. Strike-slip. 184 records. $\mathrm{FS} = 1$, $\mathrm{FN} = \mathrm{FR} = 0$.
  3. Reverse. Originally classify as thrust, reverse and reverse oblique but combine. 423 records. $\mathrm{FR} = 1$, $\mathrm{FN} = \mathrm{FS} = 0$.

  Note lack of records from normal earthquakes.
- Use data from earthquakes with focal depths $\leq 15\,\mathrm{km}$.
- Only use data from instrument shelters, non-embedded buildings with < 3 stories (< 7 if located on firm rock) and dam abutments (to enhance database even though could be some interaction with dam).
- Not sufficient data to investigate effect of tectonic environment. Exclude data from subduction zones because that is different tectonic regime than for shallow crustal earthquakes.
- Data well distributed in magnitude-distance space so do not use special statistical procedures to decouple source and path effects. Do not use weights due to uniform distribution w.r.t. M_w and distance.
- Exclude data from $> 60\,\mathrm{km}$ to avoid records with multiple reflections from lower crust.
- Vast majority of data from western USA. Some from Alaska, Canada, Greece, Iran, Italy, Japan, Mexico, New Zealand and Turkey.
- Constrain $c_7(T)$ to be monotonically varying with period because otherwise can have large changes in spectral shape at very short distances.
- Note that for $M_w < 5.8$ magnitude dependence may be due to depth-to-top (Z_{FR} and Z_{FS}) effects since small earthquakes have on average larger depth-to-top than larger earthquakes. Inter-event residuals from preliminary regression are functions of rake and depth-to-top (stronger than rake dependency) particularly for reverse earthquakes. These observations influence functional form of $f_5(Z)$.
- Use residuals from 1D simulations to define functional form for hanging wall effect ($\mathrm{HW} = 1$).
- Coefficients for nonlinear soil effects determined from analytical results because of correlations between other parameters and nonlinearity and since analytical results better constrained at high amplitudes than empirical data. Set $a_1 = 0.04\,\mathrm{g}$, $a_2 = 0.1\,\mathrm{g}$ and $\mathrm{PGA}_{min} = 0.06\,\mathrm{g}$. $\mathrm{PGA}_{non-lin}$ is expected PGA on rock ($V_{s,30} = 760\,\mathrm{m/s}$). $c_{15}(T)$, $c_{16}(T)$ and V_{lin} taken from Choi & Stewart (2005) and are not determined in regression.
- Applied limited smoothing (using piecewise continuous linear fits on log period axis) to avoid variability in predicted spectral ordinates for neighbouring periods particularly at large magnitudes and short distances.

- Examine normalized inter- and intra-event residuals w.r.t. M_w and distance (shown). Find no bias nor trends. Also plot against mechanism, site and other parameters and find no bias nor trends (not shown).

2.254 Cauzzi & Faccioli (2008), Cauzzi (2008) & Cauzzi *et al.* (2008)

- Ground-motion model is:

$$\log_{10} = a_1 + a_2 M_w + a_3 \log_{10} R + a_B S_B + a_C S_C + a_D S_D$$

  where y is in $\mathrm{m/s^2}$, $a_1 = -1.296$, $a_2 = 0.556$, $a_3 = -1.582$, $a_B = 0.22$, $a_C = 0.304$, $a_D = 0.332$ and $\sigma = 0.344$ for horizontal PGA.

- Use four site categories based on Eurocode 8:

  A Rock-like. $V_{s,30} \geq 800\,\mathrm{m/s}$. $S_B = S_C = S_D = 0$.

  B Stiff ground. $360 \leq V_{s,30} < 800\,\mathrm{m/s}$. $S_B = 1$, $S_C = S_D = 0$.

  C $180 \leq V_{s,30} < 360\,\mathrm{m/s}$. $S_C = 1$, $S_B = S_D = 0$.

  D Very soft ground. $V_{s,30} < 180\,\mathrm{m/s}$. $S_D = 1$, $S_B = S_C = 0$.

  Try to retain only records from stations of known site class but keep records from stations of unknown class (4% of total), which assume are either B or C classes. Use various techniques to extend $20\,\mathrm{m}$ profiles of K-Net down to $30\,\mathrm{m}$. Vast majority of data with $V_{s,30} \leq 500\,\mathrm{m/s}$.

- Use mechanism classification scheme of Boore & Atkinson (2007) based on plunges of P-, T- and B-axes:

Normal 16 earthquakes. $5 \leq M_w \leq 6.9$.

Strike-slip 32 earthquakes. $5 \leq M_w \leq 7.2$.

Reverse 12 earthquakes. $5.3 \leq M_w \leq 6.6$.

- Develop for use in displacement-based design.

- Select records with minimal long-period noise so that the displacement ordinates are reliable. Restrict selection to digital records because their displacement spectra are not significantly affected by correction procedure and for which reliable spectral ordinates up to at least $10\,\mathrm{s}$ are obtainable. Include 9 analogue records from 1980 Irpinia ($M_w 6.9$) earthquake after careful scrutiny of long-period characteristics.

- Use approach of Paolucci *et al.* (2008) to estimate cut-off frequencies for bandpass filtering. Compute noise index I_V for each record based on PGV and average value computed from coda of velocity time-history. Compare I_V with curves representing as a function of M_w the probability P that the long-period errors in the displacement spectrum are less than a chosen threshold. Use probability $P \geq 0.9$ and drifts in displacement spectrum $< 15\%$ using I_V from geometric mean. Rejections closely correlated with instrument type (less data from high-bit instruments rejected than from low-bit instruments). Process records by removing pre-even offset from entire time-history. Following this 57% of records satisfied criterion of Paolucci *et al.* (2008). Remaining records filtered using fourth-order acausal filter with cut-off $0.05\,\mathrm{Hz}$ after zero padding and cosine tapering. After this step records pass criterion of Paolucci *et al.* (2008). Note that filtering of 43% of records may affect reliability beyond $15\,\mathrm{s}$.

- Use data from K-Net and Kik-Net (Japan) (84%); California (5%); Italy, Iceland and Turkey (5%); and Iran (6%). Try to uniformly cover magnitude-distance range of interest. All data from $M > 6.8$ are from events outside Japan.
- Exclude data from $M_w < 5$ because probabilistic seismic hazard deaggregation analyses show contribution to spectral displacement hazard from small events is very low.
- Exclude data from $M_w > 7.2$ because 7.2 is representative of the largest estimated magnitude in historical catalogue of Italy. Most records from $M_w \leq 6.6$.
- Exclude data from subduction zone events.
- Focal depths between 2 and $22\,\mathrm{km}$. Exclude earthquakes with focal depth $> 22\,\mathrm{km}$ to be in agreement with focal depths of most Italian earthquakes.
- Use r_{hypo} for greater flexibility in seismic hazard analyses where source zones have variable depth. Exclude data from $r_{hypo} > 150\,\mathrm{km}$ based on deaggregation results.
- Test regional dependence of ground motions using analysis of variance. Divide dataset into intervals of $10\,\mathrm{km} \times 0.3M_w$ units and consider only bins with ≥ 3 records. Apply analysis for 18 bins on logarithmically transformed ground motions. Transform observed motions to site class A by dividing by site amplification factor derived by regression. Find no strong evidence for regional dependence.
- Apply pure error analysis to test: i) standard logarithmic transformation, ii) magnitude-dependence of scatter and iii) lower bound on standard deviation using only M and r_{hypo}. Divide dataset into bins of $2\,\mathrm{km} \times 0.2M_w$ units and consider only bins with ≥ 2 records (314 in total). Compute mean and standard deviation of untransformed ground motion and calculate coefficient of variation (COV). Fit linear equation to plots of COV against mean. Find no significant trend for almost all periods so conclude logarithmic transformation is justified for all periods. Compute standard deviation of logarithmically-transformed ground motions and fit linear equations w.r.t. M_w. Find that dependence of scatter on magnitude is not significant. Compute mean standard deviation of all bins and find limit on lowest possible standard deviation using only M_w and r_{hypo}.
- Aim for simplest functional form and add complexity in steps, checking the statistical significance of each modification and its influence on standard error. Try including an anelastic term, quadratic M_w dependence and magnitude-dependent decay term but find none of these is statistically significant and/or leads to a reduction in standard deviation.
- Try one-stage maximum likelihood regression but find higher standard deviation so reject it. Originally use two-stage approach of Joyner & Boore (1981).
- Find that coefficients closely match a theoretical model at long periods.
- Consider style-of-faulting by adding terms: $a_N E_N + a_R E_R + a_S E_S$ where E_x are dummy variables for normal, reverse and strike-slip mechanisms. Find that reduction in standard deviation is only appreciable for limited period ranges but keep terms in final model.
- Replace terms: $a_B S_B + a_C S_C + a_D S_D$ by $b_V \log_{10}(V_{s,30}/V_a)$ so that site amplification factor is continuous. $V_{s,30}$ available for about 85% of records. To be consistent between both approaches constrain V_a to equal $800\,\mathrm{m/s}$. Find b_V closely matches theoretical values 1 close to resonance period and 0.5 at long periods.

- Examine residuals w.r.t. r_{hypo} and M_w. Find no trends.

2.255 Chiou & Youngs (2008)

- Ground-motion model is:

$$
\begin{aligned}
\ln(y) &= \ln(y_{ref}) + \phi_1 \min\left[\ln\left(\frac{V_{S30}}{1130}\right), 0\right] \\
&+ \phi_2\{e^{\phi_3[\min(V_{S30},1130)-360]} - e^{\phi_3(1130-360)}\} \ln\left(\frac{y_{ref}e^{\eta} + \phi_4}{\phi_4}\right) \\
&+ \phi_5\left\{1 - \frac{1}{\cosh[\phi_6 \max(0, Z_{1.0} - \phi_7)]}\right\} \\
&+ \frac{\phi_8}{\cosh[0.15 \max(0, Z_{1.0} - 15)]} \\
\ln(y_{ref}) &= c_1 + [c_{1a}F_{RV} + c_{1b}F_{NM} + c_7(Z_{TOR} - 4)](1 - \mathrm{AS}) \\
&+ [c_{10} + c_{7a}(Z_{TOR} - 4)]\mathrm{AS} + c_2(M - 6) + \frac{c_2 - c_3}{c_n} \ln[1 + e^{c_n(c_M - M)}] \\
&+ c_4 \ln\{R_{RUP} + c_5 \cosh[c_6 \max(M - c_{HM}, 0)]\} \\
&+ (c_{4a} - c_4) \ln(\sqrt{R_{RUP}^2 + c_{RB}^2}) \\
&+ \left\{c_{\gamma 1} + \frac{1}{\cosh[\max(M - c_{\gamma 3}, 0)]}\right\} R_{RUP} \\
&+ c_9 F_{HW} \tanh\left(\frac{R_X \cos^2\delta}{c_{9a}}\right)\left(1 - \frac{\sqrt{R_{JB}^2 + Z_{TOR}^2}}{R_{RUP} + 0.001}\right) \\
\tau &= \tau_1 + \frac{\tau_2 - \tau_1}{2} \times [\min\{\max(M, 5), 7\} - 5] \\
\sigma &= \left\{\sigma_1 + \frac{\sigma_2 - \sigma_1}{2}[\min(\max(M, 5), 7) - 5] + \sigma_4 \times \mathrm{AS}\right\} \\
&\times \sqrt{(\sigma_3 F_{Inferred} + 0.7F_{Measured}) + (1 + \mathrm{NL})^2} \\
\text{where} \quad \mathrm{NL} &= \left(b\frac{y_{ref}e^{\eta}}{y_{ref}e^{\eta} + c}\right) \\
\sigma_T^2 &= (1 + \mathrm{NL}_0)^2\tau^2 + \sigma_{\mathrm{NL}_0}^2
\end{aligned}
$$

where y is in g, $c_2 = 1.06$, $c_3 = 3.45$, $c_4 = -2.1$, $c_{4a} = -0.5$, $c_{RB} = 50$, $c_{HM} = 3$, $c_{\gamma 3} = 4$, $c_1 = -1.2687$, $c_{1a} = 0.1$, $c_{1b} = -0.2550$, $c_n = 2.996$, $c_M = 4.1840$, $c_5 = 6.1600$, $c_6 = 0.4893$, $c_7 = 0.0512$, $c_{7a} = 0.0860$, $c_9 = 0.7900$, $c_{9a} = 1.5005$, $c_{10} = -0.3218$, $c_{\gamma 1} = -0.00804$, $c_{\gamma 2} = -0.00785$, $\phi_1 = -0.4417$, $\phi_2 = -0.1417$, $\phi_3 = -0.007010$, $\phi_4 = 0.102151$, $\phi_5 = 0.2289$, $\phi_6 = 0.014996$, $\phi_7 = 580.0$, $\phi_8 = 0.0700$, $\tau_1 = 0.3437$, $\tau_2 = 0.2637$, $\sigma_1 = 0.4458$, $\sigma_2 = 0.3459$, $\sigma_3 = 0.8$ and $\sigma_4 = 0.0663$ (η is the inter-event residual). σ_T is the total variance for $\ln(y)$ and is approximate based on the Taylor series expansion of the sum of the inter-event and intra-event variances. σ_{NL_0} is the equation for σ evaluated for $\eta = 0$. Check approximate using Monte Carlo simulation and find good (within a few percent) match to exact answer.

- Characterise sites using V_{S30}. $F_{Inferred} = 1$ if V_{S30} inferred from geology and 0 otherwise. $F_{Measured} = 1$ if V_{S30} is measured and 0 otherwise. Believe model applicable for $150 \le V_{S30} \le 1500$ m/s.

- Use depth to shear-wave velocity of $1.0\,\mathrm{km/s}$, $Z_{1.0}$, to model effect of near-surface sediments since $1\,\mathrm{km/s}$ similar to values commonly used in practice for rock, is close to reference V_{S30} and depth to this velocity more likely to be available. For stations without $Z_{1.0}$ use this empirical relationship: $\ln(Z_{1.0}) = 28.5 - \frac{3.82}{8}\ln(V_{S30}^8 + 378.7^8)$.

- Use PEER Next Generation Attenuation (NGA) database supplemented by data from TriNet system to provide additional guidance on functional forms and constraints on coefficients.

- Consider model to be update of Sadigh *et al.* (1997).

- Focal depths less than $20\,\mathrm{km}$ and $Z_{TOR} \leq 15\,\mathrm{km}$. Therefore note that application to regions with very thick crusts (e.g. $\gg 20\,\mathrm{km}$) is extrapolation outside range of data used to develop model.

- Develop model to represent free-field motions from shallow crustal earthquakes in active tectonic regions, principally California.

- Exclude data from earthquakes that occurred in oceanic crust offshore of California or Taiwan because these data have been found to be more consistent with ground motions from subduction zones. Include data from 1992 Cape Mendocino earthquakes because source depth places event above likely interface location. Exclude data from four 1997 NW China earthquakes because of large depths ($\geq 20\,\mathrm{km}$) and the very limited information available on these data. Exclude data from the 1979 St Elias earthquake because believe it occurred on subduction zone interface. Include data from the 1985 Nahanni and 1992 Roermond because believe that they occurred on boundary of stable continental and active tectonic regions.

- Assume that ground motions from different regions are similar and examine this hypothesis during development.

- Include data from aftershocks, because they provide additional information on site model coefficients, allowing for systematic differences in ground motions with mainshock motions. $\mathrm{AS} = 1$ if event aftershock and 0 otherwise.

- Exclude data from large buildings and at depth, which removes many old records. Include sites with known topographic effects since the effect of topography has not been systematically studied for all sites so many other stations may be affected by such effects. Topographic effects are considered to be part of variability of ground motions.

- Exclude records with only a single horizontal component.

- Exclude records from more than $70\,\mathrm{km}$ (selected by visual inspection) to remove effects of bias in sample.

- To complete missing information in the NGA database estimate strike, dip (δ) and rake (λ) and/or depth to top of rupture, Z_{TOR}, from other associated events (e.g. mainshock or other aftershock) or from tectonic environment. For events unassociated to other earthquake δ assigned based on known or inferred mechanisms: 90° for strike-slip, 40° for reverse and 55° for normal. For events without known fault geometries R_{RUP} and R_{JB} estimated based on simulations of earthquake ruptures based on focal mechanisms, depths and epicentral locations.

- Use M_w since simplest measure for correlating the amount of energy released in earthquake with ground motions. Develop functional form and constrain some coefficients for magnitude dependence based on theoretical arguments on source spectra and some previous analyses. Note that data are not sufficient to distinguish between various forms of magnitude-scaling.
- Exploratory analysis indicates that reverse faulting earthquakes produce larger high-frequency motions than strike-slip events. It also shows that style-of-faulting effect is statistically significant (p-values slightly less than 0.05) only when normal faulting was restricted to λ in range -120 to 60° with normal-oblique in strike-slip class. Find style-of-faulting effect weaker for aftershocks than main shocks hence effect not included for aftershocks.
- Preliminary analysis indicates statistically-significant dependence on depth to top of rupture, Z_{TOR} and that effect stronger for aftershocks therefore model different depth dependence for aftershocks and main shocks. Find that aftershocks produce lower motions than main shocks hence include this in model.
- Examine various functional forms for distance-scaling and find all provide reasonable fits to data since to discriminate between them would require more data at distances $< 10\,\mathrm{km}$. Find that data shows magnitude-dependence in rate of attenuation at all distances but that at short distances due to effect of extended sources and large distances due to interaction of path Q with differences in source Fourier spectra as a function of magnitude. Choose functional form to allow for separation of effect of magnitude at small and large distances.
- Examine distance-scaling at large distances using 666 records from 3 small S. Californian earthquakes (2001 Anza, $M4.92$; 2002 Yorba Linda, $M4.27$; 2003 Big Bear City, $M4.92$) by fitting ground motions to three functional forms. Find that two-slope models fit slightly better than a one-slope model with break point between 40 and $60\,\mathrm{km}$. Other data and simulations also show this behaviour. Prefer a smooth transition over broad distance range between two decay rates since transition point may vary from earthquake to earthquake. Constrain some coefficients based on previous studies.
- Initially find that anelastic attenuation coefficient, γ, is 50% larger for Taiwan than other areas. Believe this (and other similar effects) due to missing data due to truncation at lower amplitudes. Experiments with extended datasets for 21 events confirm this. Conclude that regression analyses using NGA data will tend to underestimate anelastic attenuation rate at large distances and that problem cannot be solved by truncated regression. Develop model for γ based on extended data sets for 13 Californian events.
- To model hanging-wall effect, use R_X, site coordinate (in km) measured perpendicular to the fault strike from the surface projection of the updip edge of the fault rupture with the downdip direction being positive and F_{HW} ($F_{HW} = 1$ for $R_X \geq 0$ and 0 for $R_X < 0$. Functional form developed based on simulations and empirical data.
- Choose reference site V_{S30} to be $1130\,\mathrm{m/s}$ because expected that no significant nonlinear site response at that velocity and very few records with $V_{S30} > 1100\,\mathrm{m/s}$ in NGA database. Functional form adopted for nonlinear site response able to present previous models from empirical and simulation studies.
- Develop functional form for $Z_{1.0}$-dependence based on preliminary analyses and residual plots.

- Model variability using random variables η_i (inter-event) and ϵ_{ij} (intra-event). Assume inter-event residuals independent and normally distributed with variance τ^2. Assume intra-event error components independent and normally distributed with variances σ_P^2 (path), σ_S^2 (site) and σ_X^2 (remaining). Assume total intra-event variance to be normally distributed with variance σ^2. Show that σ^2 is function of soil nonlinearity. Note that complete model difficult to use in regression analysis due to lack of repeatedly sampled paths and limited repeatedly sampled sites and unavailability of inference method capable of handling complicated data structure introduced by path error being included as predictor of soil amplification. Therefore apply simplification to solve problem.
- Find inter-event residuals do not exhibit trend w.r.t. magnitude. Residuals for Californian and non-Californian earthquakes do not show any trends so both sets of earthquakes consistent with model. Note that inter-event term for Chi-Chi approximately 2τ below population mean.
- Find intra-event residuals do not exhibit trends w.r.t. M, R_{RUP}, V_{S30} or y_{ref}. Note that very limited data suggests slight upward trend in residuals for $V_{S30} > 1130\,\mathrm{m/s}$, which relate to lower kappa attenuation for such sites.
- Preliminary analyses based on visual inspection of residuals suggested that standard errors did not depend on M but statistical analysis indicated that significant (p-values < 0.05) magnitude dependence is present [using test of Youngs *et al.* (1995)]. Find that magnitude dependence remains even when accounting for differences in variance for aftershocks and main shocks and for nonlinear site amplification.
- Note that in regions where earthquakes at distances $> 50\,\mathrm{km}$ are major contribution to hazard adjustments to $c_{\gamma1}$ and $c_{\gamma2}$ may be warranted.

2.256 Cotton *et al.* (2008)

- Ground-motion model is:

  $$\log[\mathrm{PSA}(f)] = a(f) + b(f)M_w + c(f)M^2 + d(f)R - \log_{10}[R + e(f) \times 10^{0.42M_w}] + S_i(f)$$

  where $\mathrm{PSA}(f)$ is in $\mathrm{m/s^2}$, $a = -5.08210$, $b = 2.06210$, $c = -0.11966$, $d = -0.00319$, $e = 0.00488$, $S = -0.01145$ and $\sigma = 0.32257$ for borehole stations (S applies for stations at $200\,\mathrm{m}$) and $a = -4.884$, $b = 2.18080$, $c = -0.12964$, $d = -0.00397$, $e = 0.01226$, $S_B = 0.16101$, $S_C = 0.27345$, $S_D = 0.45195$ and $\sigma = 0.35325$ for surface stations.

  Experiments on magnitude dependency of decay and σ reported below conducted using:

  $$\log_{10}[\mathrm{SA}_{i,j}(f)] = a(f)M_i + b(f)R_{\mathrm{rup},j} - \log_{10}(R_{\mathrm{rup},j}) + S(f)$$

  Do not report coefficients of these models.

- Use four site classes (based on Eurocode 8) for surface stations:

Class A $V_{s,30} > 800\,\mathrm{m/s}$.

Class B $360 < V_{s,30} < 800\,\mathrm{m/s}$. Use coefficient S_B.

Class C $180 < V_{s,30} < 360\,\mathrm{m/s}$. Use coefficient S_C.

Class D $V_{s,30} < 180\,\mathrm{m/s}$. Use coefficient S_D.

- Use data from boreholes to reduce influence of nonlinear site effects for investigating magnitude-dependent decay. Also derive models using surface records.
- Only use data from $< 100\,\mathrm{km}$.
- Only retain events with depth $< 25\,\mathrm{km}$ to exclude subduction earthquakes.
- Note relatively good magnitude-distance coverage.
- Visually inspect records to retain only main event if multiple events recorded and to check for glitches. Bandpass Butterworth (four poles and two passes) filter records with cut-offs 0.25 and $25\,\mathrm{Hz}$. Longest usable period of model is less than $3\,\mathrm{s}$ due to filtering.
- Derive equations using data from small ($M_w \leq 5$) earthquakes (3376 records from 310 events) and large ($M_w \geq 5$) earthquakes (518 records from 27 events) to examine ability of models to predict ground motions outside their magnitude range of applicability. Find ground motions from small events attenuate faster than from large events. Predict ground motions for M_w 4.0, 5.0 and 6.5 and 10, 30 and $99\,\mathrm{km}$. Find overestimation of ground motions for $M_w 4.0$ using model derived using data from $M_w \geq 5$ and overestimation of ground motions for $M_w 6.5$ using model derived using data from $M_w \leq 5$. Predictions for $M_w 5.0$ are similar for both models. Also compare predictions from both models and observations for $M_w 4.1$, 4.6, 5.2, 5.7, 6.5 and 7.3 and find similar results.
- Also derive models for 11 magnitude ranges: 4.0–4.2, 4.2–4.4, 4.4–4.6, 4.6–4.8, 4.8–5.0, 5.0–5.2, 5.2–5.4, 5.6–5.8, 5.8–6.8 and 6.8–7.3. Compare predictions with observations for each magnitude range and find good match. Find that decay rate depends on M_w with faster decay for small events. Plot σs from each model w.r.t. M_w and find that it has a negative correlation with M_w.
- Examine residuals w.r.t. distance. Find slight increase at large distances, which relate to magnitude dependency of attenuation.
- Note that goal of analysis was not to compete with existing models but to compare magnitude dependency of ground motions at depth and surface.
- Examine residuals w.r.t. distance and magnitude of final model. Find no trends.
- Find that σs for surface motions are larger (by about 9%) than those for motions at depth.

2.257 Humbert & Viallet (2008)

- Ground-motion model is:

$$\log(\mathrm{PGA}) = aM + bR - \log(R) + c$$

  where PGA is in $\mathrm{cm/s^2}$, $a = 0.31$, $b = -0.00091$, $c = 1.57$ and $\sigma = 0.23$.

- Use data of Berge-Thierry *et al.* (2003).
- Focal depths between 0 and $30\,\mathrm{km}$.
- Plot r_{hypo}, epicentral location and M_s from ISC against those used by Berge-Thierry *et al.* (2003). Derive standard deviation, skewness and kurtosis based on these plots.

- Account for estimated uncertainties of M and R in fuzzy regression and find same coefficients as standard regression but with estimated uncertainties and lower σ than in standard regression.
- Find that epistemic uncertainties increase at edge of magnitude-distance space.

2.258 Idriss (2008)

- Ground-motion model is:

  $$\ln[\mathrm{PSA}(T)] = \alpha_1(T)+\alpha_2(T)M-[\beta_1(T)+\beta_2(T)M]\ln(R_{rup}+10)+\gamma(T)R_{rup}+\phi(T)F$$

  where PSA is in g, $\alpha_1 = 3.7066$ and $\alpha_2 = -0.1252$ for $M \leq 6.75$, $\alpha_1 = 5.6315$ and $\alpha_2 = -0.4104$ for $6.75 < M \leq 8.5$, $\beta_1 = 2.9832$, $\beta_2 = -0.2339$, $\gamma = 0.00047$, $\phi = 0.12$ and $\sigma = 1.28 + 0.05\ln(T) - 0.08M$. σ for $M < 5$ equals σ at $M5$ and σ for $M > 7.5$ equals σ at $M7.5$. σ for $T < 0.05$ equals σ for $T = 0.05\,\mathrm{s}$. Correction factor for $V_{S30} > 900\,\mathrm{m/s}$ $\Delta\alpha_1(T) = \ln[(1 + 11T + 0.27T^2)/(1 + 16T + 0.08T^2)]$ for $0.05 \leq T \leq 10\,\mathrm{s}$ [$\Delta\alpha_1(T)$ for $T < 0.05\,\mathrm{s}$ equals $\Delta\alpha_1(0.05)$].

- Use two site classes (may derive model for $180 \leq V_{S30} < 450\,\mathrm{m/s}$ in future):

  1. $V_{S30} > 900\,\mathrm{m/s}$. 45 records. Since not enough records from stations with $V_{S30} > 900\,\mathrm{m/s}$ derive correction factor, $\Delta\alpha_1(T)$, to α_1 based on residuals for these 45 records. Find no trends in residuals w.r.t. M, R or V_{S30}.
  2. $450 \leq V_{S30} \leq 900\,\mathrm{m/s}$. 942 records (333 from stations with measured V_{S30}).

  Notes that only 29% of stations have measured V_{S30}; the rest have inferred V_{S30}s. Examine distributions of measured and inferred V_{S30}s and concluded no apparent bias by using inferred values of V_{S30}.

- Uses two mechanism categories:

Strike-slip Rake within 30° of horizontal. Includes records from normal events (rake within 30° of vertical downwards) because insufficient data to retain as separate category. $F = 0$.

Reverse Rake within 30° of vertical upwards. Includes records from reverse oblique and normal oblique events (remaining rake angles) because insufficient data to retain as separate categories. $F = 1$.

- Uses the PEER Next Generation Attenuation (NGA) database (Flat-File version 7.2).
- Excludes (to retain only free-field records): i) records from basements of any building; ii) records from dam crests, toes or abutments; and iii) records from first floor of buildings with ≥ 3 storeys.
- Excludes records from 'deep' events, records from distances $> 200\,\mathrm{km}$ and records from co-located stations.
- Only retains records with $450 \leq V_{S30} \leq 900\,\mathrm{m/s}$ for regression. Notes that initial analysis indicated that ground motions not dependent on value of V_{S30} in this range so do not include a dependency on V_{S30}.

- Uses 187 records from California (42 events), 700 records from Taiwan (Chi-Chi, 152 records, and 5 aftershocks, 548 records) and 55 records from 24 events in other regions (USA outside California, Canada, Georgia, Greece, Iran, Italy, Mexico and Turkey).
- Only 17 records from $R \leq 5\,\mathrm{km}$ and 33 from $R \leq 10\,\mathrm{km}$ (for $M \leq 7$ only 3 records from California for these distance ranges) (all site classes). Therefore, difficult to constrain predictions at short distances, particularly for large magnitudes.
- States that, from a geotechnical engineering perspective, use of V_{S30} bins is more appropriate than use of V_{S30} as an independent parameter.
- Does not investigate the influence of other parameters within the NGA Flat-File on ground motions.
- Uses PSA at $0.01\,\mathrm{s}$ for PGA (checked difference and generally less than 2%).
- Divides data into magnitude bins 0.5 units wide and conducts one-stage regression analysis for each. Compares observed and predicted PGAs at distances of 3, 10, 30 and $100\,\mathrm{km}$ against magnitude. Find that results for each magnitude bin generally well represent observations. Find oversaturation for large magnitudes due to presence of many records (152 out of 159 records for $M > 7.5$) from Chi-Chi. Does not believe that this is justified so derive α_1 and α_2 for $M > 6.75$ by regression using the expected magnitude dependency based on previous studies and 1D simulations.
- Examines residuals w.r.t. M, R and V_{S30} and concludes that for $5.2 \leq M \leq 7.2$ model provides excellent representation of data. Examine residuals for 5 Chi-Chi aftershocks and find that for $R > 15\,\mathrm{km}$ there is no bias but for shorter distances some negative bias.
- Compares predictions to observations for Hector Mine ($M7.1$), Loma Prieta ($M6.9$), Northridge ($M6.7$) and San Fernando ($M6.6$) events w.r.t. R. Finds good match.
- Comments on the insufficiency of V_{S30} as a parameter to characterise site response due to soil layering and nonlinear effects.

2.259 Lin & Lee (2008)

- Ground-motion model is:

$$\ln(y) = C_1 + C_2 M + C_3 \ln(R + C_4 \mathrm{e}^{C_5 M}) + C_6 H + C_7 Z_t$$

  where y is in g, $C_1 = -2.5$, $C_2 = 1.205$, $C_3 = -1.905$, $C_4 = 0.516$, $C_5 = 0.6325$, $C_6 = 0.0075$, $C_7 = 0.275$ and $\sigma = 0.5268$ for rock sites and $C_1 = -0.9$, $C_2 = 1.00$, $C_3 = -1.90$, $C_4 = 0.9918$, $C_5 = 0.5263$, $C_6 = 0.004$, $C_7 = 0.31$ and $\sigma = 0.6277$ for soil sites.
- Use two site categories (separate equations for each):

  Rock B and C type sites

  Soil D and E type sites
- Use two earthquake types:

Interface Shallow angle thrust events occurring at interface between subducting and overriding plates. Classified events using $50\,\mathrm{km}$ maximum focal depth for interface events. 12 events from Taiwan (819 records) and 5 from elsewhere (54 records). $Z_t = 0$.

Intraslab Typically high-angle normal-faulting events within the subducting oceanic plate. 32 events from Taiwan (3865 records) and 5 from elsewhere (85 records). $Z_t = 1$.

- Focal depths, H, between 3.94 and $30\,\mathrm{km}$ (for interface) and 43.39 and $161\,\mathrm{km}$ (for intraslab).
- Develop separate M_L-M_w conversion formulae for deep ($H > 50\,\mathrm{km}$) and shallow events.
- Use data from TSMIP and the SMART-1 array.
- Lack data from large Taiwanese earthquake (especially interface events). Therefore, add data from foreign subduction events (Mexico, western USA and New Zealand). Note that future study should examine suitability of adding these data.
- Exclude poor-quality records by visual screening of available data. Baseline correct records.
- Weight data given the number of records from different sources (Taiwan or elsewhere). Focus on data from foreign events since results using only Taiwanese data are not reliable for large magnitudes. Note that should use maximum-likelihood regression method.
- Compare predicted and observed PGAs for the two best recorded events (interface $M_w6.3$ $H = 6\,\mathrm{km}$ and intraslab $M_w5.9$ $H = 39\,\mathrm{km}$) and find good fit.
- Examine residuals and find that a normal distribution fits them very well using histograms.
- From limited analysis find evidence for magnitude-dependent σ but do not give details.
- Note that some events could be mislocated but that due to large distances of most data this should not have big impact on results.

2.260 Massa *et al.* (2008)

- Ground-motion model is:

$$\log_{10}(Y) = a + bM + c\log(R^2 + h^2)^{1/2} + s_1 S_A + s_2 S_{(B+C)}$$

where Y is in g; $a = -2.66$, $b = 0.76$, $c = -1.97$, $d = 10.72$, $s_1 = 0$, $s_2 = 0.13$, $\sigma_{eve} = 0.09$ (inter-event) and $\sigma_{rec} = 0.27$ (intra-event) for horizontal PGA and M_L; $a = -2.66$, $b = 0.76$, $c = -1.97$, $d = 10.72$, $s_1 = 0$, $s_2 = 0.13$, $\sigma_{sta} = 0.09$ (inter-site) and $\sigma_{rec} = 0.28$ (intra-site) for horizontal PGA and M_L; $a = -2.59$, $b = 0.69$, $c = -1.95$, $d = 11.16$, $s_1 = 0$, $s_2 = 0.12$, $\sigma_{eve} = 0.09$ (inter-event) and $\sigma_{rec} = 0.26$ (intra-event) for vertical PGA and M_L; $a = -2.59$, $b = 0.69$, $c = -1.95$, $d = 11.16$, $s_1 = 0$, $s_2 = 0.12$, $\sigma_{eve} = 0.08$ (inter-site) and $\sigma_{rec} = 0.26$ (intra-site) for vertical PGA and M_L; $a = -3.62$, $b = 0.93$, $c = -2.02$, $d = 11.71$, $s_1 = 0$, $s_2 = 0.12$, $\sigma_{eve} = 0.10$ (inter-event) and $\sigma_{rec} = 0.28$ (intra-event) for horizontal PGA and M_w; $a = -3.62$, $b = 0.93$, $c = -2.02$,

$d = 11.71$, $s_1 = 0$, $s_2 = 0.12$, $\sigma_{sta} = 0.11$ (inter-site) and $\sigma_{rec} = 0.29$ (intra-site) for horizontal PGA and M_w; $a = -3.49$, $b = 0.85$, $c = -1.99$, $d = 11.56$, $s_1 = 0$, $s_2 = 0.11$, $\sigma_{eve} = 0.09$ (inter-event) and $\sigma_{rec} = 0.29$ (intra-event) for vertical PGA and M_w; $a = -3.49$, $b = 0.85$, $c = -1.99$, $d = 11.56$, $s_1 = 0$, $s_2 = 0.11$, $\sigma_{eve} = 0.12$ (inter-site) and $\sigma_{rec} = 0.30$ (intra-site) for vertical PGA and M_w.

Also use functional form: $\log_{10}(Y) = a + bM + (c + eM)\log(R^2 + h^2)^{1/2} + s_1 S_A + s_2 S_{(B+C)}$ but do not report coefficients since find small values for e.

- Use three site classifications based on Eurocode 8 for the 77 stations:

  A Rock, $V_{s,30} > 800\,\mathrm{m/s}$: marine clay or other rocks (Lower Pleistocene and Pliocene) and volcanic rock and deposits. 49 stations. $S_A = 1$ and $S_{(B+C)} = 0$.

  B Stiff soil, $360 < V_{s,30} < 800\,\mathrm{m/s}$: colluvial, alluvial, lacustrine, beach, fluvial terraces, glacial deposits and clay (Middle-Upper Pleistocene); sand and loose conglomerate (Pleistocene and Pliocene); and travertine (Pleistocene and Holocene). 19 stations. $S_{(B+C)} = 1$ and $S_A = 0$.

  C Soft soil, $V_s < 360\,\mathrm{m/s}$: colluvial, alluvial, lacustrine, beach and fluvial terraces deposits (Holocene). 9 stations. $S_{(B+C)} = 1$ and $S_A = 0$.

  Because of limited records from class C combine classes B and C in regression. Note that the classification of some stations in class A could not be appropriate due to site amplification due to structure-soil interaction and topographic effects. Also note that class C is not appropriate for some stations on Po Plain due to deep sediments but that there are few data from these sites so no bias.

- Use data from various analogue and digital strong-motion (Episensor, K2, Etna, SSA-1 or SMA-1 instruments) and digital velocimetric (Mars-Lite, Mars88-MC, Reftek 130 or other instruments) networks in northern Italy, western Slovenia and southern Switzerland.

- Originally collect about 10 000 records but reduce by careful selection. Exclude data with $d_e > 100\,\mathrm{km}$ and with $M_L < 3.5$. Consider earthquakes down to $M_L 3.5$ because such earthquakes could damage sensitive equipment in industrial zones.

- 216 components (both horizontal and vertical combined) from earthquakes with $M_L > 4.5$.

- Focal depths between 1.9 and $57.9\,\mathrm{km}$. Most less than $15\,\mathrm{km}$.

- Bandpass filter using fourth-order acausal Butterworth filter with cut-offs of 0.4 and $25\,\mathrm{Hz}$ for $M_L \leq 4.5$ and 0.2 and $25\,\mathrm{Hz}$ for $M_L > 4.5$. Check using some records that PGA is not affected by filtering nor are spectral accelerations in the period range of interest. Check filtering of analogue records by visually examining Fourier amplitude spectra. Check conversion of velocimetric records to acceleration is correct by examining records from co-located instruments of different types. Exclude clipped records or records affected by noise.

- Try including a quadratic magnitude term but find that the coefficient is not statistically significant.

- Try including an anelastic attenuation term but find that coefficient is not statistically significant.

- Do not use r_{jb} since not sufficient information on rupture locations. Do not use r_{hypo} so as not to introduce errors due to unreliable focal depths.
- Do not include style-of-faulting terms because most data from reverse-faulting earthquakes (often with strike-slip component).
- Apply simple tests to check regional dependence and do not find significant evidence for regional differences in ground motions. Since records from similar earthquakes of similar mechanisms conclude that models appropriate for whole of northern Italy ($6°$–$15°$E and $43°$–$47°$N).
- Examine residuals (against earthquake and station indices, as box and whisker plots and against distance and magnitude) for sites A and sites B & C and for $M_L \leq 4.5$ and $M_L > 4.5$. Also compare predicted and observed ground motions for various magnitudes and events. Find good results.
- Suggest that for $d_e < 10\,\mathrm{km}$ and $M_L > 5.5$ $10\,\mathrm{km}$ is considered the distance at which distance saturation starts (since little data with $d_e < 10\,\mathrm{km}$ to constrain curves and predictions for shorter distances unrealistically high).
- Also derive equations for other strong-motion intensity parameters.

2.261 Mezcua *et al.* (2008)

- Ground-motion model is:

  $$\ln Y = C_1 + C_2 M + C_3 \ln R$$

  where Y is in $\mathrm{cm/s^2}$, $C_1 = 0.125$, $C_2 = 1.286$, $C_3 = -1.133$ and $\sigma = 0.69$. Only derive equation for firm soil sites due to insufficient data for other classes. For compact rock sites propose using ratio between PGA on firm soil and rock derived by Campbell (1997).

- Use three site classifications:

  1 Compact rock. Crystalline rocks (granite and basalt), metamorphic rocks (e.g. marble, gneiss, schist and quartzite) and Cretaceous and older sedimentary deposits following criteria of Campbell (1997). Similar to Spanish building code classes I and II with $400 \leq V_s \leq 750\,\mathrm{m/s}$. 23 stations.

  2 Alluvium or firm soil. Quaternary consolidated deposits. Similar to Spanish building code class III with $200 \leq V_s \leq 400\,\mathrm{m/s}$. 29 stations.

  3 Soft sedimentary deposits. 52 stations.

  Classify using crude qualitative descriptions.

- Most stations in basements of small buildings (e.g. city council offices) and therefore records are not truly free-field.
- Only consider data with $5 \leq d_e \leq 100\,\mathrm{km}$ and $M \geq 3$.
- Focal depths between 1 and $16\,\mathrm{km}$.

- Most data from $3 \leq M \leq 4$ and $d_e \leq 50\,\mathrm{km}$. Only one record with $M > 5$ and $d_e < 20\,\mathrm{km}$.
- Use hypocentral distance because no information on locations of rupture planes and since using hypocentral distance automatically limits near-source ground motions.
- Do not consider style-of-faulting since no reported mechanisms are available for most events.
- Compare predicted PGA for $M_w 5$ with observations for $4.9 \leq M_w \leq 5.1$. Find reasonable fit.

2.262 Morasca *et al.* (2008)

- Ground-motion model is:

$$\log_{10} Y = a + bM + c\log_{10} R + s_{1,2}$$

where Y is in g, $a = -4.417$, $b = 0.770$, $c = -1.097$, $D = 0$, $D_1 = 0.123$, $\sigma_{\mathrm{eve}} = 0.069$ and $\sigma_{\mathrm{rec}} = 0.339$ for horizontal PGA and intra-event sigma; $a = -4.128$, $b = 0.722$, $c = -1.250$, $D = 0$, $D_1 = 0.096$, $\sigma_{\mathrm{eve}} = 0.085$ and $\sigma_{\mathrm{rec}} = 0.338$ for vertical PGA and intra-event sigma; $a = -4.367$, $b = 0.774$, $c = -1.146$, $D = 0$, $D_1 = 0.119$, $\sigma_{\mathrm{sta}} = 0.077$ and $\sigma_{\mathrm{rec}} = 0.337$ for horizontal PGA and intra-station sigma; and $a = -4.066$, $b = 0.729$, $c = -1.322$, $D = 0$, $D_1 = 0.090$, $\sigma_{\mathrm{sta}} = 0.105$ and $\sigma_{\mathrm{rec}} = 0.335$.

- Use two site categories ($s_{1,2}$) because insufficient information to use more:

  D Rock. Average $V_s > 800\,\mathrm{m/s}$. 10 stations.

  D_1 Soil. Average $V_s < 800\,\mathrm{m/s}$. Includes all kinds of superficial deposits, from weak rocks to alluvial deposits although they are mainly shallow alluvium and soft rock (600-$700\,\mathrm{m/s}$) sites. 27 stations.

- Use data from the 2002–2003 Molise sequence from various agencies.
- Use data from accelerometers (SMA-1, 3 stations; RFT-250, 2 stations; Episensor, 10 stations) and velocimeters (CMG-40T, 4 stations; Lennartz $1\,\mathrm{s}$, 5 stations; Lennartz $5\,\mathrm{s}$, 13 stations).
- Select data with $M > 2.7$.
- Baseline and instrument correct records from analogue accelerometric instruments and filter in average bandpass 0.5–$20\,\mathrm{Hz}$ after visual inspection of the Fourier amplitude spectra. Baseline correct records from digital accelerometric instruments and filter in average bandpass 0.2–$30\,\mathrm{Hz}$ after visual inspection of the Fourier amplitude spectra. Instrument correct records from digital velocimetric instruments and filter in average bandpass 0.5–$25\,\mathrm{Hz}$ after visual inspection of the Fourier amplitude spectra.
- Most data from $r_{hypo} < 40\,\mathrm{km}$ and almost all velocimetric data from 20-$30\,\mathrm{km}$.
- Most focal depths between 10 and $30\,\mathrm{km}$.
- Relocate events using manual picks of P and S phases and a local velocity model.
- Compute M_Ls using velocimetric data.

- Note that small value of σ_{eve} suggests that the calibrated local magnitudes and relocated hypocentral locations are accurate.
- Note that small value of σ_{sta} suggests that the site classification is correct.
- Note that records from accelerometric and velocimetric instruments are similar.

2.263 Slejko *et al.* (2008)

- Ground-motion model is:

$$\begin{aligned}\log_{10} PGA &= a + (b + cM_s)M_s + (d + eM_s)\log_{10} r \\ \text{where} \quad r^2 &= D^2 + h^2\end{aligned}$$

  where PGA is in g, $a = -2.14$, $b = 0.98$, $c = -0.06$, $d = -1.88$, $e = 0.0009$, $h = 13.4$ and $\sigma = 0.35$.
- Only use data for $d_e < 100\,\mathrm{km}$ because data from larger distances only available for large earthquakes.
- Only eight records have PGA$< 0.005\,\mathrm{g}$ (standard trigger level).
- Use truncated regression analysis (Bragato, 2004) to account for bias due to non-triggering stations.

2.264 Srinivasan *et al.* (2008)

- Ground-motion model is:

$$\log(A) = c_1 + c_2 M - b\log(X + \mathrm{e}^{c_3 M})$$

  where A is in $\mathrm{cm/s^2}$, $c_1 = -1.3489$, $c_2 = 1.0095$, $b = 0.1956$, $c_3 = 0.1272$ and $\sigma = 0.20$.
- Use data from one station.
- Data from rockbursts in mines in the Kolar Gold Fields.
- Exclude records with $r_{hypo} < 1\,\mathrm{km}$ due to large change in PGAs in near-source region.
- Regress data using $\log(A) = -b\log(X) + c$ for data binned in 5 0.2 magnitude unit bins from 2.0 upwards.
- Also regress data using $\log(A) = aM - b\log(X) + c$.
- Also regress using $\log(A) = c_1 + c_2M - bc_4\log(X + \mathrm{e}^{c_3M})$ (sic) but find c_4 has a very large standard error so remove it.
- Compare predictions and observations for $M2.1$, 2.3, 2.5, 2.7 and 2.9.

2.265 Aghabarati & Tehranizadeh (2009)

- Ground-motion model is:

$$\begin{aligned}
\ln y &= c_1 + f_1(M_w) + f_2(M_w)f_3(R) + f_4(F) + \mathrm{FR}f_5(Z_{FR}) + \\
&\quad \mathrm{FS}f_6(Z_{FR}) + f_7(\mathrm{HW}, R_{JB}, M_w, \mathrm{DIP}) + \\
&\quad f_8(V_{s,30}, V_{lin}, \mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) + f_9(V_{s,30}, Z_{1.5}) \\
\text{where for } M_w \leq c_0 & \\
f_1(M_w) &= c_3(M_w - c_0) + c_8(T)(8.5 - M_w)^n \\
f_2(M_w) &= c_2(T) + c_4(M_w - c_0) \\
\text{and for } M_w > c_0 & \\
f_1(M_w) &= c_5(M_w - c_0) + c_8(T)(8.5 - M_w)^n \\
f_2(M_w) &= c_2(T) + c_6(M_w - c_0) \\
f_3(R) &= \ln\sqrt{R_{rup}^2 + c_7(T)^2} \\
f_4(F) &= c_9(T)\mathrm{FR} + c_{10}(T)\mathrm{FS} + c_{11}(T)\mathrm{FN} \\
f_5(Z_{\mathrm{FR}}) &= \begin{cases} 0 & Z_{top} \leq 2\,\mathrm{km} \\ c_{12}(T)(Z_{top} - 2)/3 & 2 < Z_{top} \leq 5\,\mathrm{km} \\ c_{12}(T) & 5 < Z_{top} \leq 10\,\mathrm{km} \\ c_{12}(T)[1 - (Z_{top} - 10)/5] & 10 < Z_{top} \leq 15\,\mathrm{km} \\ 0 & Z_{top} > 15\,\mathrm{km} \end{cases} \\
f_6(Z_{\mathrm{FS}}) &= \begin{cases} c_{13}(T)Z_{top}/2 & 0 < Z_{top} \leq 2\,\mathrm{km} \\ c_{13}(T) & 2 < Z_{top} \leq 4\,\mathrm{km} \\ c_{13}(T)[1 - (Z_{top} - 4)/2] & 4 < Z_{top} \leq 6\,\mathrm{km} \\ 0 & Z_{top} > 6\,\mathrm{km} \end{cases} \\
g_1(R_{JB}) &= \begin{cases} 1 - R_{JB}/45 & 0 \leq R_{JB} < 15\,\mathrm{km} \\ \frac{2}{3}(2 - R_{JB}/15) & 15 \leq R_{JB} < 30\,\mathrm{km} \\ 0 & R_{JB} \geq 30\,\mathrm{km} \end{cases} \\
g_2(M_w) &= \begin{cases} 0 & M_w < 6.0 \\ 2(M_w - 6) & 6.0 \leq M_w < 6.5 \\ 1 & M_w \geq 6.5 \end{cases} \\
g_3(\mathrm{DIP}) &= \begin{cases} 1 - (\mathrm{DIP} - 70)/20 & \mathrm{DIP} \geq 70 \\ 1 & \mathrm{DIP} < 70 \end{cases} \\
f_7(\mathrm{HW}, R_{JB}, M_w, \mathrm{DIP}) &= c_{14}(T)\mathrm{HW}g_1(R_{JB})g_2(M_w)g_3(\mathrm{DIP}) \\
f_8(V_{s,30}, V_{lin}, \mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) &= g_4(V_{s,30}, V_{lin}) + g_5(\mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) \\
g_4(V_{s,30}, V_{lin}) &= c_{15}(T)\ln(V_{s,30}/V_{lin}) \\
g_5(\mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) &= \begin{cases} c_{16}(T)\ln(\mathrm{PGA}_{min}/0.1) & \mathrm{PGA}_{non-lin} < a_1 \\ c_{16}(T)[\ln(\mathrm{PGA}_{min}/0.1) & \\ +a\ln(\mathrm{PGA}_{non-lin}/a_1) & \\ +b(\ln(\mathrm{PGA}_{non-lin}/a_1))^2] & a_1 \leq \mathrm{PGA}_{non-lin} \leq a_2 \\ c_{16}(T)\ln(\mathrm{PGA}_{non-lin}/0.1) & \mathrm{PGA}_{non-lin} \geq a_2 \end{cases} \\
f_9(V_{s,30}, Z_{1.5}) &= g_6(V_{s,30}, Z_{1.5}, \hat{Z}) + g_7(Z_D, Z_{1.5}) \\
g_6(V_{s,30}, Z_{1.5}, \hat{Z}) &= c_{17}(T)(1/\hat{Z})\ln(V_{s,30}/1500)\ln(Z_{1.5}) \\
\hat{Z} &= \begin{cases} 7.154 & V_{s,30} \leq 360\,\mathrm{m/s} \\ 7.154 + \frac{(4.465-7.154)[\ln(V_{s,30}/1500)-\ln(360/1500)]}{\ln(600/1500)-\ln(360/1500)} & 360 < V_{s,30} \leq 600\,\mathrm{m/s} \\ 4.465 - \frac{(2.772-4.465)[\ln(V_{s,30}/1500)-\ln(600/1500)]}{\ln(600/1500)} & V_{s,30} > 600\,\mathrm{m/s} \end{cases} \\
g_7(Z_{1.5}, Z_D) &= Z_D c_{18}(T)K_1(1 - \exp(-(Z_{1.5} - 200)/300)) + \\
&\quad Z_D c_{19}(T)K_2(1 - \exp(-(Z_{1.5} - 200)/4000))
\end{aligned}$$

where y is in g and $c_0 = 6.5$; $c_1 = 2.033$, $c_2 = -1.180$, $c_7 = 8.647$, $c_8 = -0.028$, $c_9 = -0.176$, $c_{10} = -0.266$, $c_{11} = -0.476$, $c_{12} = 0.520$, $c_{13} = -0.320$, $c_{14} = 0.400$, $c_{15} = -0.360$, $c_{17} = 0$, $c_{18} = 0$, $c_{19} = 0$, $c_{20} = 0.412$, $c_{21} = 0.427$, $K_1 = 2.260$, $K_2 = 1.040$, $V_{lin} = 760$ for horizontal PGA; and $c_1 = 2.983$, $c_2 = -1.616$, $c_7 = 9.101$,

$c_8 = -0.043$, $c_9 = -0.253$, $c_{10} = -0.463$, $c_{11} = -0.706$, $c_{12} = 0.132$, $c_{13} = -0.171$, $c_{14} = 0.513$, $c_{15} = -0.360$, $c_{17} = 0$, $c_{18} = 0$, $c_{19} = 0$, $c_{20} = 0.522$, $c_{21} = 0.537$, $K_1 = 2.260$, $K_2 = 1.040$, $V_{lin} = 760$ for vertical PGA; $\sigma = c_{20}(T)+[c_{21}(T)-c_{20}(T)]M_w$ for $5.0 \leq M_w < 7.0$ and $\sigma = c_{21}(T)$ for $M_w \geq 7.0$.

- Almost identical to Aghabarati & Tehranizadeh (2008) (see Section 2.253) but some coefficients are slightly different and they are also provided for the vertical components.
- Set $a_1 = 0.04$ g, $a_2 = 0.1$ g and $\mathrm{PGA}_{min} = 0.06$ g. $\mathrm{PGA}_{non-lin}$ is expected PGA on rock ($V_{s,30} = 760$ m/s). $c_{15}(T)$, $c_{16}(T)$ and V_{lin} taken from Choi & Stewart (2005) and are not determined in regression.

2.266 Akyol & Karagöz (2009)

- Ground-motion model is:

$$\log y = a_1 + a_2(M - 6) + b \log r + cS$$

where y is in g, $a_1 = 1.330095 \pm 0.068$, $a_2 = 0.640047 \pm 0.066$, $b = -1.65663 \pm 0.055$, $c = 0.14963 \pm 0.098$, $\sigma_1 = 0.196$ (intra-event), $\sigma_2 = 0.191$ (inter-event) and $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2} = 0.274$.

- Initially use four site classes:

1. Rock. 6 stations, 20 records.
2. Stiff soil. 11 stations, 57 records.
3. Soil. 11 stations, 32 records.
4. Deep soil. 9 stations, 59 records.

Sites classified using horizontal/vertical spectral ratios of the S-wave window of records grouped by station (details not given). Only use data with S/N ratio > 3 and smooth spectra using a nine-point moving average. Since data insufficient to obtain coefficients for all classes, combine classes 1 and 2 and classes 3 and 4 to produce categories A ($S = 0$) and B ($S = 1$) based on 77 and 91 records, respectively. Display average H/V spectral ratios for each category.

- Focal depths between 4.3 and 31.8 km.
- Note that ideally would account for faulting mechanism but for many earthquakes this parameter is unknown and also dataset is not large enough to assess its impact.
- Use data from the Turkish National Strong Motion Network of the Earthquake Research Department of the General Directorate of Disaster Affairs and the temporary Western Anatolia Seismic Recording Experiment (WASRE).
- Use r_{hypo} because fault geometries unknown for most earthquakes.
- Initially use 2123 records from all regions of Turkey. Discard records with unknown and poor estimates of magnitude, distance and/or site conditions and those outside western Anatolia. Select data with: $r_{hypo} < 200$ km, $M_w \geq 4.0$ and $\mathrm{PGA} > 0.0015$ g.

- Check low- and high-frequency noise for all records. Find that much data from SMA-1s have significant long-period noise (especially records of small earthquakes at large distances). Do not filter data but eliminate suspect records. Apply correction for instrument response. Numerically differentiate data from velociometers of WASRE network. Baseline correct all data.
- Most data from $4.5 \leq M_w \leq 5.5$ and $25 \leq r_{hypo} \leq 125\,\mathrm{km}$.
- Note that due to lack of records from $< 10\,\mathrm{km}$ cannot include fictitious depth in functional form.
- Initially include a quadratic magnitude term but this term does not improve match so drop this term.
- Test significance of site coefficients and find that they are generally significant at more than 90% confidence level.
- Plot residuals w.r.t. distance, magnitude and predicted $\log PGA$. Find systematic trends, especially for site B residuals versus M_w. Derive linear site coefficient correction terms to remove these trends (not clear how they are applied), which relate to nonlinear site response.
- Compare predictions and observations for selected earthquakes.
- Discuss reasons for differences in site effects in western Anatolia and in other regions.
- Based on results, suggest that number of stations on rock should be increase and site classifications should be re-evaluated.

2.267 Bindi *et al.* (2009a)

- Ground-motion model is:

$$\begin{aligned}\log_{10} Y &= a + b_1(M_w - M_{ref}) + b_2(M_w - M_{ref})^2 \\ &\quad +[c_1 + c_2(M_w - M_{ref}]\log_{10}\sqrt{(R_{JB} + h^2)} + e_i S_i + f_j F_j\end{aligned}$$

  where Y is in $\mathrm{cm/s^2}$ and $M_{ref} = 5.5$ (to reduce trade-offs between attenuation and source parameters), $a = 3.0761$, $b_1 = 0.1587$, $b_2 = 0.0845$, $c_1 = -1.0504$, $c_2 = -0.0148$, $h = 7.3469$, $e_1 = 0$, $e_2 = 0.2541$, $e_3 = 0.1367$, $f_1 = 0$, $f_2 = -0.0059$, $f_3 = 0.0168$, $\sigma_{event} = 0.1482$, $\sigma_{station} = 0.2083$, $\sigma_{record} = 0.1498$ and $\sigma = 0.2963$ for larger horizontal component; $a = 3.0191$, $b_1 = 0.1643$, $b_2 = 0.0674$, $c_1 = -1.0284$, $c_2 = -0.0041$, $h = 6.8963$, $e_1 = 0$, $e_2 = 0.2275$, $e_3 = 0.0774$, $f_1 = 0$, $f_2 = -0.0138$, $f_3 = 0.0005$, $\sigma_{event} = 0.1465$, $\sigma_{station} = 0.2184$, $\sigma_{record} = 0.1345$ and $\sigma = 0.2930$ for geometric mean of horizontal components; and $a = 3.0421$, $b_1 = 0.3762$, $b_2 = 0.0925$, $c_1 = -1.2350$, $c_2 = -0.0891$, $h = 9.3012$, $e_1 = 0$, $e_2 = 0.1787$, $e_3 = 0.1146$, $f_1 = 0$, $f_2 = -0.0073$, $f_3 = 0.0222$, $\sigma_{event} = 0.1266$, $\sigma_{station} = 0.2114$, $\sigma_{record} = 0.1394$ and $\sigma = 0.2831$ for vertical component.

- Use three site classes following Sabetta & Pugliese (1987, 1996):

Class 0 Rock: rock outcrops or deposits thinner than $5\,\mathrm{m}$.. 98 records. $S_1 = 1$ and $S_2 = S_3 = 0$.

Class 1 Shallow alluvium: deposits thinner than or equal to $20\,\mathrm{m}$ and thicker than $5\,\mathrm{m}$. V_s of alluvium between 400 and $800\,\mathrm{m/s}$. 62 records. $S_2 = 1$ and $S_1 = S_3 = 0$.

Class 2 Deep alluvium: deposits thicker than $20\,\mathrm{m}$. 81 records. $S_3 = 1$ and $S_1 = S_2 = 0$.

Site classification performed using verified geological, geophysical and geotechnical information, which altered the previous categorization of some stations. Data from 146 different stations. Note that only 6% of 600 Italian stations are associated with a V_s profile.

- Focal depths between 2 and $29\,\mathrm{km}$.

- Use data from Italian Accelerometric Archive (ITACA) from between 1972 and 2004, which have been carefully revised during a project funded by the Italian Department of Civil Protection. Records individually processed using individually-selected filters. Analogue records corrected for linear trend and instrument response and then band-pass filtered, selecting high-pass frequency from visual inspection of Fourier spectra (generally between 0.3 and $0.5\,\mathrm{Hz}$) and low-pass frequency chosen close to instrument frequency (generally between 20 and $25\,\mathrm{Hz}$). Digital records corrected for linear trend using entire trace (because few records have usable pre-event portion) and then band-pass filtered in the same way as analogue data (but with generally lower cut-offs, 0.1–$0.3\,\mathrm{Hz}$ and 25–$30\,\mathrm{Hz}$). Use raised cosine filter for analogue records, which often triggered on S-phase, and acausal fourth-order Butterworth for digital signals, which were padded with zeros at both ends.

- Use three faulting mechanisms:

Normal $F_1 = 1$ and $F_2 = F_3 = 0$.

Strike-slip $F_2 = 1$ and $F_1 = F_3 = 0$.

Reverse $F_3 = 1$ and $F_1 = F_2 = 0$.

Most earthquakes on normal faults in central and southern Apennines.

- Number of records per earthquake ranges from two (Ancona, 14/06/1972) to 25 (Umbria-Marche, 14/10/1997). Most earthquakes recorded by four stations or more.

- Near-source records are poorly represented: 11 records from 3 earthquakes have $r_{jb} < 5\,\mathrm{km}$ (none with $M_w > 6.4$ for which shortest r_{jb} is $7\,\mathrm{km}$).

- Most data from $10 \leq r_{jb} \leq 100\,\mathrm{km}$ and $5 \leq M_w \leq 6$.

- For Irpinia mainshock (23/11/1980), which is composed of three sub-events, used magnitude, location and time-histories of first sub-event because it can be clearly recognized.

- Assess the standard error of each coefficient using bootstrap technique based on randomly resampling, with replacement, the original dataset to obtain datasets of the same size as original (500 times). Note the coefficients using this technique are very similar.

- Note that some coefficients are not significantly different than zero (e.g. c_2 and f_j) because of the distribution of data w.r.t. M_w and mechanism.

- Examine residual plots w.r.t. M_w and r_{jb} and find no significant bias or trends.

- Examine inter-event residuals and find them within range ± 0.2 except for two earthquakes (2002 Molise second mainshock and 1990 eastern Sicily), which note could be due to inaccuracies in magnitudes and locations for these events. Find inter-event residuals for normal earthquakes show smallest dispersion, while largest variability affects strike-slip events.
- Examine inter-station residuals. Note that most are within range ± 0.3 with few with absolute values larger than 0.4. Discuss the possible reasons for these large residuals in terms of local site profiles.
- Undertake other analyses to understand the source of observed variability in ground motions.
- Also derive model for larger horizontal component using hypocentral distance and no style-of-faulting terms: $\log_{10} Y = 3.4192 + 0.4672(M_w - 5.5) + 0.1231(M_w - 5.5)^2 + [-1.2221 - 0.1643(M_w - 5.5)] \log_{10} r_{hypo} + 0.2474 S_2 + 0.1435 S_3$.
- Note that unmodelled site effects are contributing a significant proportion of the observed variability and that a more sophisticated classification scheme using depth of soil deposit, average V_s of soil deposit and resonance period could significantly reduce the inter-station variability component.

2.268 Bindi *et al.* (2009b)

- Ground-motion model is:

$$\log_{10} y = a + bM + c \log_{10} \sqrt{R^2 + h^2} + e_i S_i$$

  where y is in $\mathrm{cm/s^2}$; $a = 1.344$, $b = 0.328$, $c = -1.09$, $h = 5$, $e_0 = 0$, $e_1 = 0.262$, $e_2 = 0.096$ and $\sigma = 0.32$ using r_{epi}; and $a = 1.954$, $b = 0.193$, $c = -1.01$, $h = 5.88$, $e_0 = 0$, $e_1 = 0.264$, $e_2 = 0.144$ and $\sigma = 0.300$ using r_{jb}.

- Use three site classes following Sabetta & Pugliese (1987, 1996):

Class 0 Rock: rock outcrops or deposits thinner than $5\,\mathrm{m}$. 95 records. $S_1 = 1$ and $S_2 = S_3 = 0$.

Class 1 Shallow alluvium: deposits thinner than or equal to $20\,\mathrm{m}$ and thicker than $5\,\mathrm{m}$. V_s of alluvium between 400 and $800\,\mathrm{m/s}$. 61 records. $S_2 = 1$ and $S_1 = S_3 = 0$.

Class 2 Deep alluvium: deposits thicker than $20\,\mathrm{m}$. 79 records. $S_3 = 1$ and $S_1 = S_2 = 0$.

  Site classification performed using verified geological, geophysical and geotechnical information, which altered the previous categorization of some stations. Data from 137 different stations.

- Focal depths from 2 to $29\,\mathrm{km}$.
- Use data from Italian Accelerometric Archive (ITACA) from between 1972 and 2002, which have been carefully revised during a project funded by the Italian Department of Civil Protection, plus some data from the Northern Italy Strong Motion network (RAIS). Records individually processed. Analogue records corrected for linear trend and instrument response and then band-pass filtered, selecting high-pass frequency from visual inspection of Fourier spectra (generally between 0.3 and $0.5\,\mathrm{Hz}$) and low-pass frequency

chosen close to instrument frequency (generally between 20 and $25\,\mathrm{Hz}$). Digital records corrected for linear trend using entire trace (because few records have usable pre-event portion) and then band-pass filtered in the same way as analogue data (but with generally lower cut-offs, 0.1–$0.3\,\mathrm{Hz}$ and 25–$30\,\mathrm{Hz}$). Use raised cosine filter for analogue records, which often triggered on S-phase, and acausal fourth-order Butterworth for digital signals, which were padded with zeros at both ends. Find PGAs are consistent with those of Sabetta & Pugliese (1987, 1996) for common records.

- Very similar data to that used by Bindi *et al.* (2009a) (see Section 2.267).
- State that GMPEs are updates of those by Sabetta & Pugliese (1987, 1996).
- Examine goodness of fit of the GMPEs of Sabetta & Pugliese (1987, 1996) to the data and find that they do not adequately fit because of a too small σ and non-zero bias. Therefore, derive new GMPEs.
- Use the data from the 17 earthquakes used by Sabetta & Pugliese (1987, 1996) plus data from ten events that occurred from 1990 to 2002 with $M_w > 5.3$ and one earlier shock (Ancona 1972) that was not used by Sabetta & Pugliese (1987, 1996).
- Most new earthquakes on normal faults in central and southern Apennines with a few on strike-slip faults.
- Best sampled areas are: eastern Alps (Friuli), central-southern Apennines from Marche to Pollino and north and east Sicily.
- Majority of earthquakes recorded by more than four stations (minimum two, maximum 24).
- For Irpinia mainshock (23/11/1980), which is composed of three sub-events, used magnitude, location and time-histories of first sub-event because it can be clearly recognized.
- Only seven records from $< 5\,\mathrm{km}$. Earthquakes with $M_w > 6$ recorded at distances $> 20\,\mathrm{km}$. Best-sampled interval is 10–$100\,\mathrm{km}$ and $M_w 5$–6.
- Compare observed and predicted PGAs for $M_w 5.5$ and 6.9 and find good agreement.
- Calculate inter-event and inter-station residuals and relate observed large under- or overestimation for particular events to deep focal depths or other source characteristics. Compute $\sigma_{eve} = 0.174$ and $\sigma_{sta} = 0.222$ as inter-event and inter-station standard deviations.
- Repeat regression using 17 earthquakes of Sabetta & Pugliese (1987, 1996) but including data from additional stations that were not used by Sabetta & Pugliese (1987, 1996) and using the updated site classes. Find significant differences for $M_w 6.5$ at $20\,\mathrm{km}$.

2.269 Bragato (2009)

- Ground-motion model is:

$$\log(\mathrm{PGA}) = c_1 + c_2 M_L + c_3 \log(d_{epi}) + \sum_{k=1}^{N_s} S_k \delta_{kj}$$

where PGA is in g, $c_1 = -0.45 \pm 0.44$, $c_2 = 0.85 \pm 0.09$, $c_3 = -2.39 \pm 0.20$ and $\sigma = 0.27$ for Italy with station correction and $c_1 = -0.49 \pm 0.38$, $c_2 = 0.86 \pm 0.08$, $c_3 = -2.41 \pm 0.16$ and $\sigma = 0.38$ for Italy without station correction. S_k is correction term for kth station and δ_{kj} is Kroneker delta and N_s is number of stations in a geographical cluster. Also provides coefficients for different zones but these are not reported here.

- Uses individual site terms for each station. Data from 137 different stations.
- Investigates theoretical improvement of GMPEs for ShakeMap purposes in Italy, obtainable by accounting for regional dependencies and site effects. Notes that presented GMPEs are explorative tools rather than proposals for ShakeMap implementation because of limited data and narrow magnitude range.
- Uses data from INGV stations from between December 2005 and July 2008. Stations give homogeneous coverage in central and southern Italy and eastern Sicily but more sparse elsewhere and not existent in NE Italy.
- To exclude possible outliers, performs preliminary regression on all data and removes those records with absolute normalised standard deviations greater than three. Also excludes data from stations that have recored only one earthquake.
- Data distribution roughly uniform w.r.t. magnitude and distance.
- Tries using r_{hypo} but finds a slightly worse fit ($\sigma = 0.39$ rather than $\sigma = 0.38$), which relates to poor estimates of focal depths for some earthquakes (even though theoretically r_{hypo} should be better since it includes more information).
- Considers various partitions of available stations into different geographical zones using Delaunay triangulation. Derive a GMPE for each zone with station correction terms. Applies a genetic algorithm to minimise the standard deviation, based on the Bayesian information criterion, over the set of possible partitions. Note that this approach cannot recognise regionalised site effects. Also this method uses some data from earthquakes occurring outside the zone where the station is located. Notes that considering these complexities is not possible with current data but that most earthquakes occur in the same zone as the station. Finds that the optimal zonation has four zones.
- Investigates source and focal depth characteristics of different zones to understand the possible causes of regional variations. Concludes that observed differences are attributable to crustal structure and anelastic attenuation.
- Computes GMPEs for the six regions used in ShakeMap implementation.
- Computes GMPEs for all of Italy after correction for site amplification modelled by $V_{s,30}$-based amplification factors of Borcherdt (1994), used by ShakeMap. Find σ is unchanged. Also regress using site classes based on $V_{s,30}$s estimated from geology.
- Concludes that site effects contribute about 30% of overall standard deviation and that regional differences contribute only 4%.
- Find that station correction terms are weakly correlated to $V_{s,30}$-based amplification factors of Borcherdt (1994) used in ShakeMap to model site effects.

2.270 Hong *et al.* (2009b)

- Ground-motion models are, for interface:

$$\log_{10} Y = c_1 + c_2 M_w + c_3 R - (1.82 - 0.16 M_w)\log_{10}(R + c_5 10^{c_6 M_w}) + c_7 H$$

  where Y is in $\mathrm{cm/s^2}$, $c_1 = 2.594$, $c_2 = 0.112$, $c_3 = -0.0037$, $c_5 = 0.0075$, $c_6 = 0.474$, $c_7 = -0.0033$, $\sigma_e = 0.20$ (inter-event), $\sigma_r = 0.27$ (intra-event) and $\sigma = 0.33$ (total) for maximum response; $c_1 = 2.545$, $c_2 = 0.108$, $c_3 = -0.0037$, $c_5 = 0.0075$, $c_6 = 0.474$, $c_7 = -0.0024$, $\sigma_e = 0.20$ (inter-event), $\sigma_r = 0.27$ (intra-event); $\sigma_c = 0.10$ (random-orientation variability) and $\sigma = 0.35$ (total) for geometric mean; and, for inslab:

$$\begin{aligned} \log_{10} Y &= c_1 + c_2 M_w + c_3 R - c_4 \log_{10} R + c_5 H \\ \text{where} \quad R &= \sqrt{R_{cld}^2 + (0.0075 \times 10^{0.507 M_w})^2} \end{aligned}$$

  where $c_1 = -0.014$, $c_2 = 0.562$, $c_3 = -0.0039$, $c_5 = 0.0071$, $\sigma_e = 0.10$, $\sigma_r = 0.28$ and $\sigma = 0.30$ for maximum response; and $c_1 = -0.109$, $c_2 = 0.569$, $c_3 = -0.0039$, $c_5 = 0.0070$, $\sigma_e = 0.10$, $\sigma_r = 0.28$, $\sigma_c = 0.07$ and $\sigma = 0.30$ for geometric mean.

- All data from firm soil sites (NEHRP class B).
- Similar analysis to that of Hong & Goda (2007) (see Section 2.244) concerning orientation of major response axis but for data from Mexican subduction zone.
- Use data of García *et al.* (2005) (see Section 2.212) for inslab earthquakes.
- Focal depths, H, for interplate earthquakes are between 8 and $29\,\mathrm{km}$ and depths for inslab earthquakes are between 35 and $138\,\mathrm{km}$.
- Examine correlation of ratio of response along an arbitrary direction to the maximum response in direction of major axis w.r.t. dependent and independent parameters and find that as an approximation there is no dependency.
- Provide statistical models to describe the ratio of response along an arbitrary direction to the maximum response in direction of major axis.
- Term expressing magnitude-dependency of decay (i.e. $1.82 - 0.16 M_w$) taken from previous study as is near-source saturation term (i.e. $0.0075 \times 10^{0.507 M_w}$).

2.271 Hong *et al.* (2009a)

- Ground-motion model is:

$$\ln Y = b_1 + b_2(\mathbf{M} - 7) + b_3(\mathbf{M} - 7)^2 + [b_4 + b_5(\mathbf{M} - 4.5)]\ln[(r_{jb}^2 + h^2)^{0.5}] + \mathrm{AF}_s$$

  where Y is in g, $b_1 = 1.143$, $b_2 = 0.398$, $b_3 = 0.0$, $b_4 = -1.125$, $b_5 = 0.064$, $h = 5.6$, $\sigma_\nu = 0.150$ (inter-event), $\sigma_\epsilon = 0.438$ (intra-event) and $\sigma_T = 0.463$ (total) for geometric mean and considering spatial correlation in regression analysis; $b_1 = 1.059(0.074)$, $b_2 = 0.383(0.095)$, $b_3 = -0.006(0.014)$, $b_4 = -1.083(0.068)$, $b_5 = 0.056(0.028)$, $h = 5.7(0.40)$, $\sigma_\nu = 0.187(0.014)$ (inter-event), $\sigma_\epsilon = 0.463(0.008)$ (intra-event) and $\sigma_T = 0.500(0.008)$ (total) for randomly-orientated component ignoring spatial correlation (based on 50 runs); and $b_1 = 1.087(00.072)$, $b_2 = 0.337(0.096)$, $b_3 = -0.011(0.018)$,

$b_4 = -1.144(0.069)$, $b_5 = 0.077(0.027)$, $h = 5.6(0.38)$, $\sigma_\nu = 0.151(0.015)$ (inter-event), $\sigma_\epsilon = 0.467(0.008)$ (intra-event) and $\sigma_T = 0.491(0.008)$ (total) for randomly-orientated component considering spatial correlation (based on 50 runs). Numbers in brackets are standard deviations of coefficients.

- Use $V_{s,30}$ directly within amplification factor AF_s of Boore & Atkinson (2008) (see Section 2.240).
- Use same data and functional form as Hong & Goda (2007) (see Section 2.244).
- Modify the one- and two-stage maximum-likelihood regression methods of Joyner & Boore (1993) to consider spatial correlation of residuals from stations close together. The spatial correlation is incorporated into the covariance matrix of residuals, associated with both inter- and intra-event variability, via an empirical parametric spatial correlation model.
- Report results using two-stage approach but verify them using the one-stage method (not shown).
- Find that predictions of median ground motion not significantly affected by accounting for spatial correlation but σs do change. When spatial correlation is considered, inter-event σ decreases, intra-event σ increases and total σ decreases.

2.272 Kuehn *et al.* (2009)

- Ground-motion model is a nonphysical function (subsymbolic) (polynomial) of predictor variables (M_w, r_{jb}, $V_{s,30}$, fault mechanism and depth to top of rupture) with 48 coefficients (not reported) (14 for M_w, 5 for r_{jb}, 4 for $V_{s,30}$, 6 for rupture depth, 15 for combination of M_w and r_{jb}, intercept parameter, pseudo-depth and 2 for mechanism). Use polynomials because simple, flexible and easy to understand.
- Characterize sites using $V_{s,30}$.
- Use three faulting mechanisms:

Reverse Rake angle between 30 and $150°$. 19 earthquakes and 1870 records.

Normal Rake angle between -150 and $-30°$. 11 earthquakes and 49 records.

Strike slip Other rake angle. 30 earthquakes and 741 records.

- Use data from NGA project because best dataset currently available. Note that significant amount of metadata are missing. Discuss the problems of missing metadata. Assume that metadata are missing at random, which means that it is possible to perform unbiased statistical inference. To overcome missing metadata only select records where all metadata exist, which note is only strictly valid when metadata are missing completely at random.
- Select only records that are representative of free-field conditions based on Geomatrix classification C1.
- Exclude some data from Chi-Chi sequence due to poor quality or co-located instruments.

- Exclude data from $r_{jb} > 200\,\mathrm{km}$ because of low engineering significance and to reduce correlation between magnitude and distance. Also note that this reduces possible bias due to different attenuation in different regions.
- In original selection one record with $M_w5.2$ and the next at $M_w5.61$. Record with $M_w5.2$ had a dominant role for small magnitudes so it was removed.
- Discuss the problem of over-fitting (modelling more spurious details of sample than are supported by data generating process) and propose the use of generalization error (estimated using cross validation), which directly estimates the average prediction error for data not used to develop model, to counteract it. Judge quality of model primarily in terms of predictive power. Conclude that approach is viable for large datasets.
- State that objective is not to develop a fully-fledged alternative NGA model but to present an extension to traditional modelling strategies, based on intelligent data analysis from the fields of machine learning and artificial intelligence.
- For k-fold cross validation, split data into k roughly equal-sized subsets. Fit model to $k-1$ subsets and compute prediction error for unused subset. Repeat for all k subsets. Combine k prediction error estimates to obtain estimate of generalization error. Use $k = 10$, which is often used for this approach.
- Use r_{jb} because some trials with simple functional form show that it gives a smaller generalization error than, e.g., r_{rup}.
- Start with simple functional form and add new terms and retain those that lead to a reduction in generalization error.
- Note that some coefficients not statistically significant at 5% level but note that 5% is an arbitrary level and they result in lower generalization error.
- Compare generalization error of final model to that from fitting the functional form of Akkar & Bommer (2007b) and an over-fit polynomial model with 58 coefficients and find they have considerably higher generalization errors.
- After having found the functional form, refit equation using random-effects regression.
- Note that little data for $r_{jb} < 5\,\mathrm{km}.$
- Note that weakness of model is that it is not physically interpretable and it cannot be extrapolated. Also note that could have problems if dataset is not representative of underlying data generating process.
- Note that problem with magnitude scaling of model since available data is not representative of underlying distribution.

2.273 Mandal *et al.* (2009)

- Ground-motion model is:

$$\ln(Y) = a + bM_w - \ln(r_{jb}^2 + c^2)^{1/2} + dS$$

where Y is in g, $a = -7.9527$, $b = 1.4043$, $c = 19.82$, $d = -0.0682$ and $\sigma = 0.8243$.

- Use two site classes:

$S = 0$ Rock/stiff. Relatively compact Jurassic formations. Believe that $V_{s,30} > 760\,\mathrm{m/s}$.

$S = 1$ Soil. Alluvium or fragile Tertiary and Quaternary formations. Believe that $250 \leq V_{s,30} < 760\,\mathrm{m/s}$.

  Classify using geological information.

- Fault ruptures mainly less than $40\,\mathrm{km}$ depth.
- Use data from engineering seismoscopes (SRR) from 2001 $M_w 7.7$ Bhuj earthquake and from strong-motion (20) and broadband (8) instruments of its aftershocks ($3.1 \leq M_w \leq 5.6$), which correct for instrument response. Earthquakes recorded at 3 to 15 stations.
- All data from aftershocks from $r_{epi} < 80\,\mathrm{km}$ and all data from mainshock from $r_{jb} \leq 44\,\mathrm{km}$.
- Relocate earthquakes using local 1D velocity model. Report average error of $1\,\mathrm{km}$ in epicenter and $1.5\,\mathrm{km}$ in focal depth.
- Estimate seismic moments (from which compute M_w) and other source parameters, assuming Brune spectra, using spectral analysis of SH waves from transverse components. Report uncertainty of 0.05–0.1 units.
- Report that faults well mapped so believe r_{jb}s are quite reliable.
- Plot residuals w.r.t. r_{jb}. Find greater scatter in residuals for $0 \leq r_{jb} \leq 30\,\mathrm{km}$, which could be related to amplification/noise in data from stations in Kachchh sedimentary basin. Note lower scatter for range $100 \leq r_{jb} \leq 300\,\mathrm{km}$ is unreliable due to lack of data.
- State equation less reliable for $100 \leq r_{jb} \leq 300\,\mathrm{km}$ due to lack of data.
- Plot observations and predictions for $M_w 3.5$, 4.1, 4.5, 5.6 and 7.7 and find fair match. Note that insufficient data to judge relation between $M_w 5.6$ and 7.7. Find reasonable match to six records from 29 March 1999 Chamoli earthquake ($M_w 6.5$) but poor match (predictions lower than observations) to single record from 10 December 1967 Koyna earthquake ($M_w 6.3$).

2.274 Moss (2009)

- Ground-motion model is that of Chiou & Youngs (2008) (see Section 2.255). Also uses same data. This model selected since sufficiently complete and readily available at time of analysis.
- Notes that most GMPEs treat input variables as exact, neglecting uncertainties associated with measurements of V_s, M_w and r. These uncertainties propagate through regression and result in model overestimating inherent variability in ground motion. Presents method to estimate uncertainty of input parameters and incorporate it into regression procedure using Bayesian framework.
- Follows on from Moss & Der Kiureghian (2006) (see Section 2.231).
- Presents the Bayesian framework used for regression. This procedure is iterative and leads to results that are slightly non-unique.

- Uses the functional form and data of Boore *et al.* (1997) for feasibility study. Repeat analysis of Boore *et al.* (1997) and confirm published results. Then assumes uncertainties on $V_{s,30}$ and r_{jb} of coefficient of variation (COV) of 15% and find that intra-event σ reduces by 15 and 17% respectively. Also introduces uncertainty of standard deviation of 0.1 on M_w and finds inter-event σ reduces by 20%. Overall finds reduction of 37%. Finds that coefficients obtained are similar to those found with standard regression.

- Discusses in detail the epistemic uncertainties associated with measurements of V_s and the procedures and data used to quantify intra- and inter-method variabilities of measurement techniques. Conclusions are used to estimate standard deviations for each measurement of $V_{s,30}$ based on the measurement method, soil type and $V_{s,30}$ and possible bias in measurements are corrected using derived empirical formulae.

- Briefly discusses epistemic uncertainties associated with estimates of M_w. Plots standard deviations of M_w estimates w.r.t. M_w for NGA database. Finds negative correlation, which relates to a number of factors. Regression on data gives $\sigma_{M\_M} = -0.1820\ln(M) + 0.4355$, which is combined with reported time component of standard deviation $\sigma_{M_t} = 0.081$ thus: $\sigma_M = \sqrt{\sigma_{M\_M}^2 + \sigma_{M_t}}$ to give the overall uncertainty in M_w. Notes that more work is needed to quantify uncertainty in M_w. Does not include the uncertainty in M_w in regression results.

- Discusses epistemic uncertainties in source-to-site distances and estimates different components of uncertainty. Notes that more work is needed to quantify uncertainties and, therefore, does not account for this uncertainty in regression.

- Replicates results reported by Chiou & Youngs (2008). Then assumes an average $V_{s,30}$ measurement uncertainty of COV$\approx 27\%$ and reports the decrease in σ (4%).

- Compare results to approximate solutions from first-order second-moment and Monte Carlo techniques, which are useful since they are quicker than the full Bayesian regression. Find reasonable match in results.

- Notes that the smaller σs could have a large impact on PSHAs for long return periods.

2.275 Pétursson & Vogfjörd (2009)

- Ground-motion model is

$$\log_{10}(\mathrm{PGA}) = a\log_{10}(r + k10^{gM+eM^2}) + bM + c + dM^2$$

  where PGA is in g, $a = -2.26$, $b = 1.28$, $c = -2.85$, $d = -0.0437$, $e = -d/a = -0.0194$, $g = -b/a = 0.569$, $k = 0.0309$ and $\sigma = 0.302$.

- Detailed information on site conditions is not available hence do not include site terms in model.

- Focal depths between 0.04 and $9.49\,\mathrm{km}$ with most $\leq 6\,\mathrm{km}$.

- Use data from SIL national seismic network (3-component velocimeters) converted to acceleration. Most instruments are short-period Lennartz sensors (7 with corner frequency of $1\,\mathrm{Hz}$ and 35 with corner frequency of $0.2\,\mathrm{Hz}$). 6 to 8 broadband sensors (CMG-3T, CMG-40T, CMG-ESP and STS2 with corner frequencies at 0.008 and $0.033\,\mathrm{Hz}$).

Full-scale amplitude of stations between $0.3\,\mathrm{cm/s}$ and $1.25\,\mathrm{cm/s}$. Hence, at near-source distances records are often saturated and unusable. Most data have sampling rate of $100\,\mathrm{Hz}$ but some records are sampled at $20\,\mathrm{Hz}$. First, remove instrument response. Next, high-pass filter (for short-period records use cut-off of $0.15\,\mathrm{Hz}$ and for broadband used $0.1\,\mathrm{Hz}$). Finally, differentiate velocity to obtain acceleration. Do not use data sampled at $20\,\mathrm{Hz}$ nor data from distances $> 100\,\mathrm{Hz}$ from Lennartz $1\,\mathrm{Hz}$ sensors.

- Note that magnitudes of earthquaks with $M > 3$ are generally underestimated by SIL system, which is designed to monitor microseismicity. Therefore, use 5 of 6 largest earthquakes with teleseismic (Global CMT) M_w estimates to calibrate the local moment magnitudes M_{Lw} used for study.

- Develop model for use in ShakeMap and real-time aftershock hazard mapping applications.

- Most earthquakes from the Hengill region in 1997 and 1998. 7 are on Reykjanes Peninsula and 6 in the South Iceland Seismic Zone (mainly from sequence in 2000, which provides three largest earthquakes used).

- Note that model of Ágústsson *et al.* (2008) is significantly flawed. Use same data but remove data from Reykjanes Ridge and Myrdalsjokull because of uncertainties in magnitude estimates for these earthquakes.

- Data selected based on magnitude and number and quality of usable waveforms.

- Most data from $M_{Lw} \leq 5$ and $r_{epi} > 20\,\mathrm{km}$ and distribution shows effect of saturation of records for larger ($M_{Lw} > 5$) earthquakes for $r_{epi} < 20\,\mathrm{km}$. Correlation coefficient between M_{Lw} and $\log r_{epi}$ is 0.24. 39% of data is from 5 to $50\,\mathrm{km}$.

- Also derive most using simpler functional form: $\log_{10}(\mathrm{PGA}) = -2.08\log_{10}(r) - 0.0431M^2 + 1.21M - 2.96$ with $\sigma = 0.304$.

- In SW Iceland large earthquakes usually occur on NS faults. Hence, examine effect of radiation pattern. Add radiation pattern variable to model so that all earthquakes were assumed to take place on NS-striking vertical strike-slip faults. Find that, as predicted by theory, the coefficient multiplying this term was close to unity and standard deviation was significantly reduced. However, find that this term led to worse fit for some earthquakes and so it was dropped.

- Examine effect of instrument type using residual plots. Find that data from Lennartz $1\,\mathrm{Hz}$ sensors and Nanometrics RD3 $0.5\,\mathrm{Hz}$ digitizers from $> 100\,\mathrm{km}$ were lower than predicted, which led to them being excluded.

- Find that observations from hve station are consistently lower than predicted, which relate to strong attenuation in Western Volcanic Zone. Make similar observations for ada, bru and mok, which relate to propagation through crust and upper mantle of Eastern Volcanic Zone. Find data from snb station is consistently higher due to strong Moho relections from Hengill region earthquakes at about $130\,\mathrm{km}$.

- Try form $\log_{10}(\mathrm{PGA}) = a\log_{10}\sqrt{r_{epi}^2 + k^2} + bM + c$ but find very small k. Also try form of Fukushima & Tanaka (1990) but find higher standard deviations.

- Discuss the theoretical basis of coefficient g and its constraints w.r.t. a and b. Initial regression with g as free parameter led to coefficients very close to $g = -b/a$ (PGA independent of M at source) and, therefore, impose this as constraint.
- Try weighted regression to correct for uneven magnitude and distance distribution but these are dropped since data follows magnitude distribution expected in SW Iceland and also run risk of putting too much emphasis on erroneous recordings.
- Find that residuals are approximately normally (in terms of $\log_{10}$) distributed, using normal Q-Q plots.
- Compare predictions and observations for some magnitude ranges and for each earthquake grouped by geographical region.
- Fit $\log_{10}(\mathrm{PGA}) = a \log r_{epi} + \ldots$ using only data from $< 150\,\mathrm{km}$ and $M_{Lw} > 4.7$ and find $a = -1.70$. Relate difference in distance scaling to lack of far-field data.
- Believe that model can be used between 0 and $380\,\mathrm{km}$.

2.276 Rupakhety & Sigbjörnsson (2009)

- Ground-motion model is:

$$\log_{10}(S_a) = b_1 + b_2 M_w + b_3 \log_{10} \sqrt{d^2 + b_4^2} + b_5 S$$

  where S_a is in g, $b_1 = -1.038$, $b_2 = 0.387$, $b_3 = -1.159$, $b_4 = 2.600$, $b_5 = 0.123$ and $\sigma = 0.287$.
- Use two site classes:

Rock Eurocode 8 site class A, $V_{s30} > 800\,\mathrm{m/s}$. 64 records. $S = 0$.

Stiff soil Eurocode 8 site class B (21 records) or C (8 records), $180 < V_{s30} < 800\,\mathrm{m/s}$. $S = 1$.

- Most records from $M_w < 6.6$.
- Assume magnitude-independent decay rate, linear magnitude dependency and no anelastic term because insufficient data to do otherwise.
- Data primarily from south Iceland supplemented with records from Greece, Turkey and Slovenia.
- Exclude distant records because of low engineering significance and to minimise differences in anelastic decay between regions.
- Records from strike-slip earthquakes except for data from one oblique-faulting Icelandic earthquake. Select earthquakes from extensional regimes.
- Do not exclude data from buildings because of limited records. Exclude data from Thjorsarbru Bridge because they show clear structural effects and site dependent conditions not characteristic of study area as a whole.
- Records processed using individually-chosen filters.

- Show comparisons between predicted and observed normalized ground motions w.r.t. distance and conclude that selected functional form fits the data sufficiently well.
- Note that correlation matrix shows strong multi-collinearity between coefficients, which implies imprecise estimates of regression coefficients meaning that outside the range of the data predictions could be unreliable.

2.277 Akkar & Bommer (2010)

- Ground-motion model is:

$$\log y = b_1 + b_2 M + b_3 M^2 + (b_4 + b_5 M) \log \sqrt{R_{\mathrm{jb}}^2 + b_6^2} + b_7 S_S + b_8 S_A + b_9 F_N + b_{10} F_R$$

where y is in $\mathrm{cm/s^2}$, $b_1 = 1.04159$, $b_2 = 0.91333$, $b_3 = -0.08140$, $b_4 = -2.92728$, $b_5 = 0.28120$, $b_6 = 7.86638$, $b_7 = 0.08753$, $b_8 = 0.01527$, $b_9 = -0.04189$, $b_{10} = 0.08015$, $\sigma_1 = 0.2610$ (intra-event) and $\sigma_2 = 0.0994$ (inter-event).

- Use three site categories:

Soft soil $S_S = 1$, $S_A = 0$.

Stiff soil $S_A = 1$, $S_S = 0$.

Rock $S_S = 0$, $S_A = 0$.

- Use three faulting mechanism categories:

Normal $F_N = 1$, $F_R = 0$.

Strike-slip $F_N = 0$, $F_R = 0$.

Reverse $F_R = 1$, $F_N = 0$.

- Use same data as Akkar & Bommer (2007b) (see Section 2.235) but repeat regression analysis for pseudo-spectral acceleration (rather than for spectral displacement), assuming homoscedastic variability, reporting the coefficients to five decimal places and not applying any smoothing. These changes made due to shortcomings revealed in GMPEs of Akkar & Bommer (2007b) after their use in various projects that required, for example, extrapolation outside their magnitude range of applicability and work reported in Bommer *et al.* (2007) (see Section 2.239) and other studies.
- Examine total, inter- and intra-event residuals w.r.t. M_w and r_{jb} and found no apparent trends (shown for a selection of periods). Note that some plots suggest magnitude-dependent variability but insufficient data to constrain it.

2.278 Akkar & Çağnan (2010)

- Ground-motion model is [based on base model of Abrahamson & Silva (1997, 2008)]:

$$
\begin{aligned}
\ln(Y) &= a_1 + a_2(\mathbf{M} - c_1) + a_4(8.5 - \mathbf{M})^2 + [a_5 + a_6(\mathbf{M} - c_1)] \ln \sqrt{R_{jb}^2 + a_7^2} \\
&\quad + a_8 F_N + a_9 F_R + F_S \quad \text{for} \quad \mathbf{M} \leq c_1 \\
\ln(Y) &= a_1 + a_3(\mathbf{M} - c_1) + a_4(8.5 - \mathbf{M})^2 + [a_5 + a_6(\mathbf{M} - c_1)] \ln \sqrt{R_{jb}^2 + a_7^2} \\
&\quad + a_8 F_N + a_9 F_R + F_S \quad \text{for} \quad \mathbf{M} > c_1 \\
\text{where} \quad F_S &= F_{LIN} + F_{NL} \\
F_{LIN} &= b_{lin} \ln \left(\frac{V_{S30}}{V_{ref}} \right) \\
F_{NL} &= b_{nl} \ln \left(\frac{\text{pga}_{\text{low}}}{0.1} \right) \quad \text{for} \quad \text{pga4nl} \leq 0.03\,\text{g} \\
F_{NL} &= b_{nl} \ln \left(\frac{\text{pga}_{\text{low}}}{0.1} \right) + c \left[\ln \left(\frac{\text{pga4nl}}{0.03} \right) \right]^2 + d \left[\ln \left(\frac{\text{pga4nl}}{0.03} \right) \right]^3 \\
&\quad \text{for} \quad 0.03 < \text{pga4nl} \leq 0.09\,\text{g} \\
F_{NL} &= b_{nl} \ln \left(\frac{\text{pga4nl}}{0.1} \right) \quad \text{for} \quad \text{pga4nl} > 0.09\,\text{g}
\end{aligned}
$$

  where Y is in cm/s^2, $a_1 = 8.92418$, $a_2 = -0.513$, $a_3 = -0.695$, $a_4 = -0.18555$, $a_5 = -1.25594$, $a_6 = 0.18105$, $a_7 = 7.33617$, $a_8 = -0.02125$, $a_9 = 0.01851$, $\sigma = 0.6527$ (intra-event), $\tau = 0.5163$ (inter-event) and $\sigma_{Tot} = \sqrt{\sigma^2 + \tau^2} = 0.8322$ and $b_{lin} = -0.36$, $b_1 = -0.64$ and $b_2 = -0.14$ [taken from Boore & Atkinson (2008)]. Fix $c_1 = 6.5$. pga4nl is predicted PGA in g for $V_{s,30} = 760\,\text{m/s}$. See Boore & Atkinson (2008) for b_{nl}, c and d [not repeated by Akkar & Çağnan (2010)].

- Characterise sites using $V_{s,30}$ and use the site response terms of Boore & Atkinson (2008) because of their simplicity and fairly good performance for data (demonstrated by intra-event residual plots and their distributions that do not show clear trends, except perhaps for $V_{s,30} > 720\,\text{m/s}$). Majority of records from NEHRP C ($360 \leq V_{s,30} \leq 760\,\text{m/s}$) and D ($180 \leq V_{s,30} < 360\,\text{m/s}$) sites with very few from sites with $V_{S30} \geq 760\,\text{m/s}$. All sites have measured $V_{s,30}$ values.

- Use three faulting mechanisms:

Normal $F_N = 1$, $F_R = 0$. 28% of records.

Strike-slip $F_N = 0$, $F_R = 0$. 70% of records.

Reverse/thrust $F_N = 0$, $F_R = 1$. 2% of records.

- Focal depths between about 0 and $50\,\text{km}$ with most between 5 and $20\,\text{km}$.

- Use data from the recently compiled Turkish strong-motion database (Akkar *et al.* , 2010), for which the independent parameters were carefully reassessed.

- Note that there are many singly-recorded earthquakes.

- Vast majority of data from $M_w < 6$ and $r_{jb} > 10\,\text{km}$.

- Explore several functional forms (not shown). Try to keep balance between rigorous model (for meaningful and reliable estimations) and a robust expression (for wider implementation in engineering applications).

- Data from 102 mainshocks (346 records) and 35 aftershocks (88 records).
- Bandpass filter records using method of Akkar & Bommer (2006).
- Compare PGAs from unfiltered and filter records and find negligible differences.
- Note that aim of study is not to promote the use of poorly-constrained local models.
- Use pure error analysis (Douglas & Smit, 2001) to investigate magnitude-dependence of σ. Find strong dependence of results on binning strategy (including some bins that suggest increase in σ with magnitude) and, therefore, disregard magnitude dependency.
- Derive GMPEs using data with minimum thresholds of $M_w 3.5$, $M_w 4.0$, $M_w 4.5$ and $M_w 5.0$ to study influence of small-magnitude data on predictions. Find that equation using $M_w 5.0$ threshold overestimates PGAs derived using lower thresholds; however, ranking of predictions from GMPEs using thresholds of $M_w 3.5$, $M_w 4.0$ and $M_w 4.5$ is not systematic.
- Note that due to limited records from reverse-faulting earthquakes, the coefficient a_9 needs refining using additional data.
- Examine inter-event residuals for PGA, $0.2\,\mathrm{s}$ and $1\,\mathrm{s}$ w.r.t. M_w and intra-event residuals w.r.t. r_{jb} and $V_{s,30}$. Fit straight lines to residuals and also compute bias over ranges of independent variables. Test significance of trends at 5% level. Find no significant bias w.r.t. M_w nor w.r.t. r_{jb}. For $V_{s,30}$ for $1\,\mathrm{s}$ find significant overestimation for $V_{s,30} > 450\,\mathrm{m/s}$, which relate to linear site term. Suggest linear site term needs adjustment using Turkish data.
- Compute inter-station residuals and identify 9 outlier stations, which are those with residuals mainly outside range generally observed.
- Examine bias of residuals for mainshock and aftershock records. Find weak evidence for overestimation of aftershock motions but this is not significant at the 5% level.
- Combine Turkish and Italian data from ITACA (1004 records) and derive GMPEs using same functional form, except using site classes rather than $V_{s,30}$ directly, to test observed differences between local and global GMPEs.
- Compare focal depth distributions, using histograms with intervals of $5\,\mathrm{km}$, of the datasets for various GMPEs. Compute mean and standard deviations of M_w for each depth bin. Find that records from Turkey and Italian are on average deeper than those for other GMPEs, which seems to explain lower observed motions. Conclude that focal depth can be important in explaining regional differences.

2.279 Arroyo *et al.* (2010)

- Ground-motion model is:

$$
\begin{aligned}
\ln \mathrm{SA}(T) &= \alpha_1(T) + \alpha_2(T) M_w + \alpha_3(T) \ln\left[\frac{E_1(\alpha_4(T) R) - E_1(\alpha_4(T)\sqrt{R^2 + r_0^2})}{r_0^2}\right] \\
r_0^2 &= 1.4447 \times 10^{-5} \mathrm{e}^{2.3026 M_w}
\end{aligned}
$$

where SA is in $\mathrm{cm/s^2}$, $E_1(x)$ is the exponential integral function, $\alpha_1 = 2.4862$, $\alpha_2 = 0.9392$, $\alpha_3 = 0.5061$, $\alpha_4 = 0.0150$, $b = -0.0181$, $\sigma = 0.7500$ (total), $\sigma_e = 0.4654$ (inter-event) and $\sigma_r = 0.5882$ (intra-event).

- All data from rock (NEHRP B) sites. Data from stations with known, significant site amplification and those located in volcanic belt are excluded. Use H/V ratios to verify that stations are all on generic rock. Data from 56 different stations.
- Focal depths between 10 and $29\,\mathrm{km}$.
- Functional form is based on the analytical solution of a circular finite-source model and body waves, which also defines expression for r_0 (the radius of the circular fault based on Brune's model) using a stress drop of $100\,\mathrm{bar}$ in order to keep functional form as simple as possible. Note that functional form allows for oversaturation, whose existence is questionable.
- Select data of interplate, thrust-faulting events (interface) from permanent networks between 1985 and 2004 on the Pacific coast between Colima and Oaxaca (majority of data from Guerrero but some data from other regions, especially Oaxaca). Data from near-trench earthquakes whose high-frequency radiation is anomalously low are excluded. To focus on ground motions of engineering interest, exclude data from small ($M_w \leq 5.5$) with few records that are only from distant stations ($R > 100\,\mathrm{km}$). Exclude data from $> 400\,\mathrm{km}$ (use a larger distance than usual because of previously observed slow decay). To reduce potential variability of data, select only one record from two stations recording the same earthquake at less than $5\,\mathrm{km}$ (based on visual inspection of data).
- Data from 12–$19\,\mathrm{bit}$ digital accelerographs (66% of data), which have flat response down to less than $0.1\,\mathrm{Hz}$, and $24\,\mathrm{bit}$ broadband seismographs (34% of data), which have flat response for velocities between 0.01 and $30\,\mathrm{Hz}$. Broadband data mainly from $M_w < 6$ and distances $> 100\,\mathrm{km}$. Sampling rates between 80 and $250\,\mathrm{Hz}$. Instrumental responses and sampling rates mean data reliable up to $30\,\mathrm{Hz}$.
- Roughly 45% of records from 20–$100\,\mathrm{km}$. Only 16 records from $< 25\,\mathrm{km}$ and only 5 from 3 earthquakes with $M_w > 7$ and, therefore, note that any anomalous records will strongly influence results in this distance range. State that more near-source data from large Mexican interplate earthquakes needed.
- Use Bayesian regression that accounts, for linear functions, for these correlations: 1) intra-event, 2) between coefficients and 3) between different periods. To linearize function perform regression as: for a given period and value of α_4, compute coefficients α_1, α_2 and α_3 through Bayesian analysis and iterate for different values of α_4 to find the value that gives best fit to data. This is repeated for each period. Note that this means the regression is not fully Bayesian. To obtain prior information on coefficients α_1, α_2 and α_3 use random vibration theory and theoretical expression for Fourier amplitude spectrum. Define other required prior parameters (covariances etc.) using previous studies. Smooth α_4 w.r.t. period. Discuss differences between prior and posterior values and not that final results not over-constrained to mean prior values.
- Find that model systematically overestimates in whole period range but since less than 5% consider bias acceptable.
- Plot residuals w.r.t. M_w, distance and depth and find no significant trend. Note that even though focal depth is not included in model there is no significant dependence on it.

- Adjust observed near-source PGAs to a common distance of $16\,\mathrm{km}$ and include data from $M_w 2.5$–4.9 from r_{hypo} between 16 and $37\,\mathrm{km}$. Compare to predictions. Note the large scatter (more than an order of magnitude) so note that statistical significance is low. Note that model matches observations reasonably well.

2.280 Bindi *et al.* (2010)

- Ground-motion model is:

$$\begin{aligned}\log_{10} Y &= a + b_1(M_w - M_{ref}) + b_2(M_w - M_{ref})^2 \\ &\quad +[c_1 + c_2(M_w - M_{ref})]\log_{10}\sqrt{(R^2+h^2)} + e_i S_i + f_j F_j\end{aligned}$$

  where Y is in $\mathrm{cm/s^2}$ and $M_{ref} = 4.5$; $a = 3.7691$, $b_1 = 0.0523$, $b_2 = -0.1389$, $c_1 = -1.9383$, $c_2 = 0.4661$, $h = 10.1057$, $C_0 = 0$, $C_1 = 0.2260$, $C_2 = 0.1043$, $\sigma_{eve} = 0.2084$, $\sigma_{sta} = 0.2634$ and $\sigma = 0.3523$ for horizontal PGA using r_{jb}; $a = 3.2191$, $b_1 = 0.1631$, $b_2 = -0.0765$, $c_1 = -1.7613$, $c_2 = 0.3144$, $h = 9.1688$, $C_0 = 0$, $C_1 = 0.1938$, $C_2 = 0.1242$, $\sigma_{eve} = 0.2080$, $\sigma_{sta} = 0.1859$ and $\sigma = 0.3384$ for vertical PGA using r_{jb}; $a = 3.750$, $b_1 = 0.1180$, $b_2 = -0.1147$, $c_1 = -1.9267$, $c_2 = 0.4285$, $h = 10.0497$, $C_0 = 0$, $C_1 = 0.2297$, $C_2 = 0.1022$, $\sigma_{eve} = 0.2103$, $\sigma_{sta} = 0.2666$ and $\sigma = 0.3555$ for horizontal PGA using r_{epi}; and $a = 3.2015$, $b_1 = 0.2482$, $b_2 = -0.0428$, $c_1 = -1.7514$, $c_2 = 0.2588$, $h = 9.1513$, $C_0 = 0$, $C_1 = 0.1983$, $C_2 = 0.1230$, $\sigma_{eve} = 0.1917$, $\sigma_{sta} = 0.1877$ and $\sigma = 0.3241$ for vertical PGA using r_{epi}[15].

- Use three site classes following Sabetta & Pugliese (1987, 1996):

  C_0 Rock. Corresponding to NEHRP A and B categories. 104 stations. $S_1 = 1$ and $S_2 = S_3 = 0$.

  C_1 Shallow sediment: deposits thinner than or equal to $20\,\mathrm{m}$ and thicker than $5\,\mathrm{m}$. V_s of sediment lower than $800\,\mathrm{m/s}$. 47 stations. $S_2 = 1$ and $S_1 = S_3 = 0$.

  C_2 Deep sediment: deposits thicker than $20\,\mathrm{m}$. 55 stations. $S_3 = 1$ and $S_1 = S_2 = 0$.

  Site classification performed using verified geological, geophysical and geotechnical information but of varying detail. Note that classification between C_1 and C_2 is a simple but efficient method to identify sites with amplifications at frequencies larger or smaller than 2–$5\,\mathrm{Hz}$. Data from 206 different stations.

- Use four faulting mechanism classes:

  Normal 50 earthquakes.

  Strike-slip 12 earthquakes.

  Reverse 17 earthquakes.

  Unknown 28 earthquakes.

  Find that mechanism coefficients are not significantly different than zero and, therefore, remove them.

- Focal depths between 0 and $29.21\,\mathrm{km}$.

[15] There is an inconsistency between the names given to the site coefficients in the tables of this article (C_0, C_1 and C_2) and those used to describe the functional form (e_0, e_1 and e_2).

- Use data from Italian Accelerometric Archive (ITACA) from between 1972 and 2007, which have been carefully revised during a project funded by the Italian Department of Civil Protection, plus some data from the Northern Italy Strong Motion network (RAIS). Records individually processed using acausal fourth-order Butterworth filters with cut-offs selected by visual inspection of Fourier spectra.
- Select records with $r_{jb} < 100\,\mathrm{km}$ from earthquakes with $M_w \geq 4$ recorded at two or more stations.
- $M_w \leq 6$ are well sampled for $r_{jb} > 5\,\mathrm{km}$, particularly for $4 \leq M_w \leq 4.6$. No data from $r_{jb} < 10\,\mathrm{km}$ from earthquakes with $M_w > 6$.
- Compare PGAs and r_{jb} for common records with Sabetta & Pugliese (1987). For PGA find similar values, indicating that the different processing applied results in consistent results. For r_{jb} find significant differences for distances shorter than $20\,\mathrm{km}$, which attribute to improvements in knowledge of source geometries.
- Examine inter-event and inter-station residuals. Find most inter-event errors are between -0.2 and 0.2 with a few events (e.g. 2002 Molise) with largely or over- or under-estimated.
- When comparing observations and predictions for Irpina ($M_w 6.9$) 1980 earthquake state that comparisons unreliable for $r_{jb} < 10\,\mathrm{km}$ due to lack of data.
- Compare predictions and observations for the 23/12/2008 ($M_w 5.4$) northern Apennines earthquake mainshock to Parma and its $M_w 4.9$ aftershock (both with focal depth $> 20\,\mathrm{km}$ and reverse mechanism), which were not used to develop GMPEs. 33 records ($32 \leq r_{epi} \leq 217\,\mathrm{km}$) of mainshock and 26 ($9 \leq r_{epi} \leq 217\,\mathrm{km}$) records of aftershock. Find the most observations fall within $\pm 1\sigma$ but some for $30 \leq r_{epi} \leq 60\,\mathrm{km}$ are over-estimated by up to one order of magnitude.
- Note importance of improving site categorization to reduce σ_{sta}.

2.281 Cua & Heaton (2010)

- Ground-motion model is:

$$\begin{aligned}\log Y &= aM + b[R_1 + C(M)] + d\log[R_1 + C(M)] + e \\ R_1 &= \sqrt{R^2 + 9} \\ C(M) &= c_1 \exp[c_2(M-5)][\tan^{-1}(M-5) + \pi/2]\end{aligned}$$

  where Y is in $\mathrm{cm/s^2}$, $a = 0.73$, $b = -7.2 \times 10^{-4}$, $c_1 = 1.16$, $c_2 = 0.96$, $d = -1.48$, $e = -0.42$ and $\sigma = 0.31$ for rock and $a = 0.71$, $b = -2.38 \times 10^{-3}$, $c_1 = 1.72$, $c_2 = 0.96$, $d = -1.44$, $e = -2.45 \times 10^{-2}$ and $\sigma = 0.33$ for soil.

- Use two site classes using southern California site classification map based on $V_{s,30}$ of Wills *et al.* (2000):

Rock Class BC and above, $V_{s,30} > 464\,\mathrm{m/s}$. 35 SCSN stations with 958 records. 50 records from NGA.

Soil Class C and below, $V_{s,30} \leq 464\,\mathrm{m/s}$. No data from very soft soils. 129 SCSN stations with 2630 records. 1557 records from NGA.

and develop independent equations for each since sufficient data.

- Use data from the Southern California Seismic Network (SCSN) (150 stations) and COSMOS (6 events) supplemented by the Next Generation Attenuation (NGA) dataset. Mainly used broadband data from SCSN except when clipped, when accelerometric data is used instead.
- Correct records for gain and baseline and convert to acceleration using differentiation, if needed.
- For SCSN data use S-wave envelope amplitudes and not PGAs directly. Note that should be comparable to true PGAs.
- Constrain c_2 to be approximately unity within regression.
- Develop conversion factors for converting between different definitions of horizontal component and their σs.
- Compare predicted and observed PGAs for ranges: $6.5 < M < 7.5$ (predictions for $M7.0$), $4.0 < M < 6.0$ (predictions for $M5.0$) and $M < 3.0$ (predictions for $M2.5$) and find good match.
- Examine residuals and find no significant trends w.r.t. distance or magnitude.
- Compute station-specific site corrections for SCSN stations that recorded more than 3 times. Applying these corrections for rock PGA produces a 20% reduction in σ (to 0.24).

2.282 Douglas & Halldórsson (2010)

- Ground-motion model is the same as Ambraseys *et al.* (2005a) (see Section 2.207) with the addition of a term $b_{11}\mathrm{AS}$, where $\mathrm{AS} = 1$ for an aftershock record and 0 otherwise. Find predicted motions from aftershocks slightly smaller than from mainshocks.
- Examine total residual plots, biases and standard deviations of rederived GMPEs of Ambraseys *et al.* (2005a) with magnitude-independent σ with earthquake classified as aftershock or other. Do not find significant differences in residuals between aftershocks and the rest of the data.
- Discuss the use of aftershock data when developing GMPEs.

2.283 Faccioli *et al.* (2010)

- Ground-motion model is:

$$\begin{aligned}\log_{10}\mathrm{DRS}(T) &= a_1 + a_2 M_w + a_3 \log_{10}(R_{rup} + a_4 10^{a_5 M_w}) \\ &+ a_B S_B + a_C S_C + a_D S_D + a_N E_N + a_R E_R + a_S E_S\end{aligned}$$

where $\mathrm{DRS}(T)$ is in $\mathrm{cm/s^2}$, $a_1 = -1.18$, $a_2 = 0.559$, $a_3 = -1.624$, $a_4 = 0.018$, $a_5 = 0.445$, $a_B = 0.25$, $a_C = 0.31$, $a_D = 0.33$, $a_N = -0.01$, $a_R = 0.09$, $a_S = -0.05$, $k_1 = 2.03$, $k_2 = -0.138$, $k_3 = -0.962$ and $\sigma = 0.36$[16].

[16]Typographical error in article (E_I should be E_S).

- Use four Eurocode 8 classes:

  A Rock. $S_B = S_C = S_D = 0$.

  B Stiff soil. $S_B = 1$, $S_C = S_D = 0$.

  C Medium-dense soil deposits. $S_C = 1$, $S_B = S_D = 0$.

  D Soft soil deposits. $S_D = 1$, $S_B = S_C = 0$.

- Use three faulting mechanisms:

Normal $E_N = 1$, $E_R = E_S = 0$.

Reverse $E_R = 1$, $E_N = E_S = 0$.

Strike-slip $E_S = 1$, $E_N = E_R = 0$.

- Update of Cauzzi & Faccioli (2008) (see Section 2.254) using more data and r_{rup} rather than r_{hypo} because this is more appropriate close to large earthquakes.
- Find that differences between r_{rup} and r_{hypo} are not statistically significant for $M_w \leq 5.7$ so use r_{hypo} below this threshold.
- Most data from Japan.
- Use a subset of data to decide on the best functional form, including forms with M_w^2 and/or distance-saturation terms and site classes or $V_{s,30}$ directly.
- Carefully examine (not show) fit between predicted and observed spectra in near-source region and find distance-saturation term provides best fit.
- Note that M_w^2 term has negligible impact on σ but improves predictions for large M_w. Drops M_w^2 from final functional form.
- Find site terms significantly reduce σ.
- Effect of style of faulting terms on σ is minimal but does improve predictions.
- Note that functional form means that one-step rather than two-step approach must be used that means that effects of magnitude and distance cannot be decoupled and σs are larger.
- Compare predictions and observations for two records and find overprediction in one case and underprediction in other, which relate to the approximation of the model and not an error in determination of coefficients.
- Test model against data ($4.5 \leq M_w \leq 6.9$, $r_{rup} < 150\,\mathrm{km}$) from the Italian Accelerometric Archive (ITACA) using residual plots and method of Scherbaum *et al.* (2004). Find that good ranking is obtained using approach of Scherbaum *et al.* (2004). Find trends in residual plots, which correct using functions, with coefficients k_1, k_2 and k_3, fit to the residuals. k_i can be added to a_i to obtain corrected coefficients (a_4 and a_5 are unchanged).
- Note that improvements to Cauzzi & Faccioli (2008) are still ongoing.

2.284 Graizer *et al.* (2010)

- Ground-motion model is:

$$\begin{aligned}\ln(Y) &= \ln(A) - 0.5\ln\left[\left(1-\frac{R}{R_2}\right)^2 + 4D_2^2\frac{R}{R_2}\right] - 0.5\ln\left[\left(1-\sqrt{\frac{R}{R_3}}\right)^2 + 4D_3^2\sqrt{\frac{R}{R_3}}\right] + \\ & b_v\ln\left(\frac{V_{s,30}}{V_A}\right) - 0.5\ln\left[\left(1-\sqrt{\frac{R}{R_5}}\right)^2 + 4D_5^2\sqrt{\frac{R}{R_5}}\right] \\ A &= [c_1\arctan(M+c_2)+c_3]F \\ R_2 &= c_4M + c_5 \\ D_2 &= c_6\cos[c_7(M+c_8)] + c_9 \\ R_5 &= c_{11}M^2 + c_{12}M + c_{13}\end{aligned}$$

  where Y is in g, $c_1 = 0.14$, $c_2 = -6.25$, $c_3 = 0.37$, $c_4 = 3.67$, $c_5 = -12.42$, $c_6 = -0.125$, $c_7 = 1.19$, $c_8 = -6.15$, $c_9 = 0.525$, $c_{10} = -0.16$, $c_{11} = 18.04$, $c_{12} = -167.9$, $c_{13} = 476.3$, $D_5 = 0.7$, $b_v = -0.24$, $V_A = 484.5$, $R_3 = 100\,\mathrm{km}$ and $\sigma = 0.83$. Coefficients c_4, c_5, c_{10}–c_{13} and D_5 are newly derived as is σ — the others are adopted from GMPE of Graizer & Kalkan (2007). $D_3 = 0.65$ for $Z < 1\,\mathrm{km}$ and 0.35 for $Z \geq 1\,\mathrm{km}$.

- Use sediment depth Z to model basin effects.

- Use two faulting mechanisms:

Strike-slip and normal $F = 1.00$

Reverse $F = 1.28$

- Update of GMPE of Graizer & Kalkan (2007) (see Section 2.245) to model faster attenuation for $R > 100\,\mathrm{km}$ using more data (from the USGS-Atlas global database).

- Compare data binned into 9 magnitude ranges with interval 0.4 and find good match.

- Note that large σ due to variability in Atlas database.

- Using data binned w.r.t. M_w and into 25 distance bins (with spacing of $20\,\mathrm{km}$) derive these models for σ: $\sigma = -0.043M + 1.10$ and $\sigma = -0.0004R + 0.89$.

- Examine residual plots w.r.t. distance, M_w and $V_{s,30}$ and find no trends.

2.285 Hong & Goda (2010)

- Ground-motion models are the same as Hong *et al.* (2009b) (see Section 2.270) for interplate and inslab Mexican earthquakes and Hong & Goda (2007) and Goda & Hong (2008) (see Section 2.244) for intraplate Californian earthquakes. Coefficients are: $b_1 = 1.271$, $b_2 = 0.337$, $b_3 = 0.0$, $b_4 = -1.119$, $b_5 = 0.063$, $h = 5.9$, $\sigma_\eta = 0.190$, $\sigma_\epsilon = 0.463$, $\sigma_T = 0.501$ and $\mathrm{PGA}_{ref} = \exp[1.0 + 0.446(M_w - 7) - 0.888\ln(r_{jb}^2 + 6.3^2)^{0.5}]$ for major principal axis and $b_1 = 0.717$, $b_2 = 0.454$, $b_3 = -0.009$, $b_4 = -1.000$, $b_5 = 0.041$, $h = 5.0$, $\sigma_\eta = 0.182$ (inter-event), $\sigma_\epsilon = 0.441$ (intra-event), $\sigma_T = 0.477$ (total) and $\mathrm{PGA}_{ref} = \exp[0.532 + 0.518(M_w - 7) - 0.846\ln(r_{jb}^2 + 5.6^2)^{0.5}]$ for minor principal axis for intraplate California; $c_1 = -3.005$, $c_2 = 0.555$, $c_3 = -0.00392$, $c_4 = 0.0079$,

$\sigma_\eta = 0.106$ (inter-event), $\sigma_\epsilon = 0.285$ (intra-event) and $\sigma_T = 0.304$ (total) for major principal axis and $c_1 = -3.253$, $c_2 = 0.575$, $c_3 = -0.00380$, $c_4 = 0.0079$, $\sigma_\eta = 0.121$, $\sigma_\epsilon = 0.270$ (intra-event) and $\sigma_T = 0.296$ (total) for minor principal axis for inslab Mexican earthquakes; and $d_1 = -0.396$, $d_2 = 0.113$, $d_3 = -0.00361$, $d_4 = 0.0075$, $d_5 = 0.474$, $d_6 = -0.0040$, $\sigma_\eta = 0.193$ (inter-event), $\sigma_\epsilon = 0.264$ (intra-event) and $\sigma_T = 0.327$ (total) for major principal axis and $d_1 = -0.653$, $d_2 = 0.125$, $d_3 = -0.00356$, $d_4 = 0.0075$, $d_5 = 0.474$, $d_6 = -0.00177$, $\sigma_\eta = 0.200$ (inter-event), $\sigma_\epsilon = 0.273$ and $\sigma_T = 0.339$ (total) for minor principal axis for interface Mexican earthquakes.

- Similar analysis to that of Hong & Goda (2007) (see Section 2.244) and Hong *et al.* (2009b) (see Section 2.270) concerning orientation of major response axis.
- Conduct analyses for intraplate Californian (Hong & Goda, 2007) and interface and inslab Mexican data (Hong *et al.* , 2009b).
- Discuss impact of different definitions of horizontal component on predicted ground motions and σs for the three types of earthquake.

2.286 Jayaram & Baker (2010)

- Ground-motion model is that of Campbell & Bozorgnia (2008b) (see Section 2.241).
- Use same data as Campbell & Bozorgnia (2008b) (see Section 2.241).
- Modify the random-effects regression method of Abrahamson & Youngs (1992) to account for spatial correlation defined by a pre-defined empirical model dependent on separation distance or derived during the regression analysis. Prefer the use of a predefined empirical model for various reasons.
- To provide baseline model for comparison, refit model of Campbell & Bozorgnia (2008b) using random-effects regression ignoring spatial correlation. Find minor differences with reported coefficients of Campbell & Bozorgnia (2008b), which relate to manual coefficient smoothing.
- Find intra-event σ increases and inter-event σ decreases but total σ remains roughly the same when spatial correlation is accounted for. Provide theoretical justification for difference in σs if spatial correlation between records is considered or not.
- Do not report coefficients, only provide graphs of σs.
- State that, because regression coefficients are not significant different if spatial correlation is accounted for, the regression procedure can be simplified.
- Discuss the implications of findings on risk assessments of spatially-distributed systems.

2.287 Montalva (2010)

- Ground-motion model is for combined model using both surface and borehole records[17] (same as Boore & Atkinson (2008)):

$$\begin{aligned}
\mu^A_{med} &= F_m + F_d + F_{site}\mathrm{Surf}_{flag} + F_{100}\mathrm{S100}_{flag} + F_{200}\mathrm{S200}_{flag} \\
F_m &= e_1 + e_5(M_w - M_h) + e_6(M_w - M_h)^2 \quad \text{for} \quad M_w \leq M_h \\
F_m &= e_1 + e_7(M_w - M_h) \quad \text{for} \quad M_w \geq M_h \\
F_d &= [c_1 + c_2(M_w - M_h)]\log(R/R_{ref}) + c_3(R - R_{ref}) \\
R &= \sqrt{R^2_{RUP} + h^2} \\
F_{site} &= b_{lin}\ln(V_{s30}/V_{ref}) + \mathrm{bh800}\ln(\mathrm{h800}/h_{ref}) \\
F_{100} &= a_{100} + b_{100}\ln(V_{s30}/V_{ref}) + c_{100}\ln(\mathrm{Vshole}/\mathrm{Vshole}_{ref}) \\
F_{200} &= a_{200} + b_{200}\ln(V_{s30}/V_{ref}) + c_{200}\ln(\mathrm{Vshole}/\mathrm{Vshole}_{ref})
\end{aligned}$$

  where μ^A_{med} is in g, $M_{ref} = 4.5$, $R_{ref} = 1\,\mathrm{km}$, $V_{ref} = 760\,\mathrm{m/s}$, $h_{ref} = 60\,\mathrm{m}$ and $\mathrm{Vshole}_{ref} = 3000\,\mathrm{m/s}$ (reference values); $c_1 = -1.2534$, $c_2 = 0.4271$, $c_3 = -0.0140$, $e_1 = -0.0663$, $e_5 = -0.5997$, $e_6 = -0.5012$, $e_7 = 0$, $b_{lin} = -0.4665$, $\mathrm{bh800} = -0.1801$, $a_{100} = -1.4372$, $a_{200} = -1.6518$, $b_{100} = -0.0269$, $b_{200} = -0.1884$, $c_{100} = -0.2666$, $c_{200} = -0.3793$, $\phi = 0.6293$ (intra-event) for $M_w < 5$, $\phi = 0.6202$ (intra-event) for $M_w > 6.5$, $\tau = 0.4929$ (inter-event) for $M_w < 5$, $\tau = 0.9164$ (inter-event) for $M_w > 6.5$ (linear interpolation of ϕ and τ between $M_w 5$ and 6.5) and $\tau^* = 0.4981$ for $M_w > 6.5$ (computed using inter-event residuals corrected for the observed bias using a linear term) [18].

- Characterise sites by $V_{s,30}$, depth to reach V_s of $800\,\mathrm{m/s}$ ($\mathrm{h800}$) and V_s at bedrock (Vshole).

- Uses an NGA functional form to reflect state of the art in ground-motion prediction and the form of Boore & Atkinson (2008) specifically because it can be constrained by the data.

- Extension of analysis by Rodriguez-Marek & Montalva (2010) (see Section 4.173).

- Analysis conducted to investigate single-site variability of ground motions.

- Data from KiK-net on surface and at depth as processed by Pousse *et al.* (2005) and Cotton *et al.* (2008) (see Sections 4.126 and 2.256 for details). Note that although Cotton *et al.* (2008) state that spectral accelerations up to $3\,\mathrm{s}$ can be used, in fact some spectral accelerations at long periods are less than the number of decimals used for storing the data. Hence limit analysis to periods $< 1.3\,\mathrm{s}$.

- Majority of data is for $M_w \leq 6.1$, which will have an impact on the regression.

- Presents histogram of $V_{s,30}$ at surface stations: peak around $500\,\mathrm{m/s}$ with very few records for $V_{s,30} > 1000\,\mathrm{m/s}$.

- Presents histogram of borehole depths: almost all at 100 and $200\,\mathrm{m}$. Use flag to indicate borehole instrument depth $\leq 150\,\mathrm{m}$ or $> 150\,\mathrm{m}$.

[17] Same functional form is used for separate models using only surface and only borehole records but without the flags indicating surface or borehole stations.

[18] M_h not clearly stated in report but could be 5.6 (p. 150).

- Presents histogram of $V_{s,30}$ at borehole stations: roughly uniformly distributed between $1000\,\mathrm{m/s}$ and $2500\,\mathrm{m/s}$ with some higher and lower.
- Notes that geographical distribution of earthquakes shows clusters that could enable a further separation of source and path effects from site effects in future studies.
- Only uses data from earthquake that were recorded by ≥ 5 stations to adequately constrain inter-event residuals.
- Uses multiple step regression method. First, uses only data from earthquakes recorded by > 100 stations to constrain c_3 and h by maximum-likelihood regression (after fixing c_1 to a value between -0.2 and -1.1 and fixing c_2 to 0). Next finds M_h and e_7. Originally find that e_7 is negative (oversaturation) but note that lack of data from large earthquakes so constrain it to be positive. M_h is chosen by inspection. Rest of coefficients found by random-effects regression.
- Combined model assumes source and path terms are independent of near-surface layering, which note is desired from a phenomenological view.
- Plots inter-event residuals against M_w and find overestimation for $M_w > 6.5$ due to constraint that ground motions do not oversaturate. Plots inter-event residuals against depth and find that motions from deeper events underestimated, which relate to less attenuation than shallower events and possibly different stress drops in shallow and deep earthquakes.
- Plots intra-event residuals against M_w and r_{rup} and site parameters and find no trends. However, finds trend in residuals from earthquakes recorded at $r_{rup} < 20\,\mathrm{km}$, which relate to lack of near-fault-effects and nonlinear soil terms. Also finds decreasing variation in the intra-event residuals for $r_{rup} > 200\,\mathrm{km}$.
- Examines correlation between normalised inter- and intra-event residuals and concludes that they are uncorrelated.
- Finds combined, surface and borehole inter-event residuals well correlated.
- Recommends use of combined model rather than the surface or borehole only models.
- Computes single-station residuals and σs, by defining site terms for each station based on intra-event residuals, from 131 stations that recorded > 10 earthquakes. Finds slight magnitude dependence of residuals. Finds no correlation between intra-event residuals corrected by site terms and inter-event residuals. Examine in detail single-station residuals, associated σs and their various components w.r.t. to their use in PSHA without the ergodic assumption. Report these single-station σs: surface $\phi = 0.4967$, borehole $\phi = 0.5060$, surface $\sigma = 0.6725$ and borehole $\sigma = 0.6684$.
- Examine effect of selecting data from a station-to-event azimuthal bracket of 8° and finds that sigma is reduced.

2.288 Ornthammarath *et al.* (2010), Ornthammarath (2010) & Ornthammarath *et al.* (2011)

- Ground-motion model is:

$$\log y = b_1 + b_2 M_w + b_3 \log(\sqrt{r_{jb}^2 + b_4^2}) + b_5 S_S$$

where y is in $\mathrm{m/s^2}$, $b_1 = -2.622$, $b_2 = 0.643$, $b_3 = -1.249$, $b_4 = 3.190$, $b_5 = 0.344$, $\sigma_{event} = 0.0723$, $\sigma_{station} = 0.1198$ and $\sigma_{record} = 0.1640$.

- Use two site classes:

  S Stiff soil, $360 \leq V_{s30} \leq 750\,\mathrm{m/s}$, 3 stations, 13 records, $S_S = 1$

  R Rock, $V_{s30} > 750\,\mathrm{m/s}$, 28 stations, 68 records, $S_S = 0$

  V_{s30} at most stations unknown so use local site conditions to classify stations. Note that there are no deep alluvium soil deposits in Iceland so basin effects are limited.

- Focal depths between 10 and $15\,\mathrm{km}$.
- All earthquakes have strike-slip mechanisms since the South Iceland Seismic Zone is transform zone.
- Develop model to investigate source of variability in ground motions in Iceland not for seismic hazard assessments.
- Data well distributed with respect to M_w, r_{jb} and earthquakes (between 9 and 18 records per event).
- Only use high-quality data, following visual inspection.
- Dropped anelastic attenuation term since it was positive.
- Dropped quadratic magnitude term since insufficient data to constrain it, as were magnitude-dependent distance decay terms.
- Note that low σ could be due to limited records from only six earthquake of similar sizes and mechanisms and from a small geographical area and few stations.
- Examines single-station residuals (site terms) and single-station σs for a few stations.

2.289 Ulutas & Ozer (2010)

- Ground-motion model is[19]:

$$\log A = C_1 + C_2 M_w - \log_{10}(r_{rup} + 0.0183 \times 10^{0.4537 M_w}) + \log C_3 r_{rup}$$

  where A is in g, $C_1 = -2.7809$, $C_2 = 0.5344$, $C_3 = -0.0015$ and $\sigma = 0.392$ (stated to be in terms of natural logarithms although GMPE presented in terms of $\log$).

- Purpose of develop GMPE is for rapid assessment of PGA following earthquake and, therefore, no distinction made between rock and soil sites.
- Focal depths between 2 and $22\,\mathrm{km}$.
- All records from 1999 Kocaeli (Izmit) and Düzce earthquakes and their aftershocks from 132 permanent and temporary stations.
- Earthquakes are mainly strike-slip but some have normal mechanisms. Believe that model should only be used for these types of mechanisms.

[19]Although r_{rup} is used in Equation 4 of the paper it is probable that the distance metric is actually r_{jb} since they default to r_{epi} when the fault geometric is not known.

- Baseline and instrument correct records. Examine Fourier amplitude spectra to select the high- and low-pass filters. Use the Basic strong-motion Accelerogram Processing (BAP) software: high-cut filtering with a cosine shape and then low-cut bi-directional second-order Butterworth filtering (after padding with zeros).
- Select data with $M_w \geq 4$.
- Distance saturation term ($0.0183 \times 10^{0.4537 M_w}$) within the $\log_{10}$ given by square root of rupture area estimated by regression analysis on areas for the two mainshocks and the equations of Wells & Coppersmith (1994) for other earthquakes.
- Compare observed and predicted PGAs for different M_w.
- State that GMPE can be used for $4 \leq M_w \leq 7.5$ and distances $\leq 200\,\mathrm{km}$.
- Note that site effects should be included within the model but currently lack of information.

Chapter 3

General characteristics of GMPEs for PGA

Table 1 gives the general characteristics of published attenuation relations for peak ground acceleration. The columns are:

H Number of horizontal records (if both horizontal components are used then multiply by two to get total number)

V Number of vertical components

E Number of earthquakes

$M_{\min}$ Magnitude of smallest earthquake

$M_{\max}$ Magnitude of largest earthquake

M scale Magnitude scale (scales in brackets refer to those scales which the main M values were sometimes converted from, or used without conversion, when no data existed), where:

- m_b Body-wave magnitude
- M_C Chinese surface wave magnitude
- M_{CL} Coda length magnitude
- M_D Duration magnitude
- M_{JMA} Japanese Meteorological Agency magnitude
- M_L Local magnitude
- M_{Lw} Local moment magnitude reported by the Icelandic Meterological Office
- M_{bLg} Magnitude calculated using Lg amplitudes on short-period vertical seismographs
- M_s Surface-wave magnitude
- M_w Moment magnitude

$r_{\min}$ Shortest source-to-site distance

$r_{\max}$ Longest source-to-site distance

r scale Distance metric, where (when available the *de facto* standard abbreviations of Abrahamson & Shedlock (1997) are used):

- r_c Distance to rupture centroid
- r_{epi} Epicentral distance
- r_E Distance to energy centre
- r_{jb} Distance to projection of rupture plane on surface (Joyner & Boore, 1981)
- r_{hypo} Hypocentral (or focal) distance
- r_q Equivalent hypocentral distance (EHD) (Ohno *et al.* , 1993)
- r_{rup} Distance to rupture plane
- r_{seis} Distance to seismogenic rupture plane (assumes near-surface rupture in sediments is non-seismogenic) (Campbell, 1997)

S Number of different site conditions modelled, where:

- C Continuous classification
- I Individual classification for each site

C Use of the two horizontal components of each accelerogram [see Beyer & Bommer (2006)], where:

- 1 Principal 1
- 2 Principal 2
- A Arithmetic mean
- B Both components
- C Randomly chosen component
- D50 $\mathrm{GMrotD50}$ (Boore *et al.* , 2006).
- G Geometric mean
- I50 $\mathrm{GMrotI50}$ (Boore *et al.* , 2006).
- L Larger component
- M Mean (not stated what type)
- N Fault normal
- O Randomly oriented component
- P Fault parallel
- Q Quadratic mean, $\sqrt{(a_1^2 + a_2^2)/2}$, where a_1 and a_2 are the two components (Hong & Goda, 2007)
- R Resolved component
- S $\sqrt{(a_1 + a_2)/2}$, where a_1 and a_2 are the two components (Reyes, 1998)
- U Unknown
- V Vectorially resolved component, i.e. square root of sum of squares of the two components
- V3 Vectorially resolved component including vertical, i.e. square root of sum of squares of the three components

R Regression method used, where:

- 1 Ordinary one-stage

- 1B Bayesian one-stage (Ordaz *et al.* , 1994)
- 1M Maximum likelihood one-stage or random-effects (Abrahamson & Youngs, 1992; Joyner & Boore, 1993)
- 1W Weighted one-stage
- 1WM Weighted maximum-likelihood one-stage
- 2 Two-stage (Joyner & Boore, 1981)
- 2M Maximum likelihood two-stage (Joyner & Boore, 1993)
- 2W Two-stage with second staged weighted as described in Joyner & Boore (1988)
- O Other (see section referring to study)
- U Unknown (often probably ordinary one-stage regression)

M Source mechanisms (and tectonic type) of earthquakes (letters in brackets refer to those mechanism that are separately modelled), where:

- A All (this is assumed if no information is given in the reference)
- AS Aftershock
- B Interslab
- C Shallow crustal
- F Interface
- HW Hanging wall
- I Intraplate
- M Mining-induced
- N Normal
- O Oblique or odd (Frohlich & Apperson, 1992)
- R Reverse
- S Strike-slip
- T Thrust
- U Unspecified

'+' refers to extra records from outside region used to supplement data. (...) refer either to magnitudes of supplementing records or to those used for part of analysis. * means information is approximate because either read from graph or found in another way.

Illustration 1: Characteristics of published peak ground acceleration relations

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Esteva & Rosenblueth (1964)	W. USA	46*	-	U	U	U	U	15*	450*	r_{hypo}	1	U	U	A
Kanai (1966)	California & Japan	U	-	U	U	U	U	U	U	r_{rup}	C	U	U	A
Milne & Davenport (1969)	W. USA	U	-	U	U	U	U	U	U	r_{epi}	1	U	U	A
Esteva (1970)	W. USA	U	-	U	U	U	U	15*	500*	r_{hypo}	1	U	U	A
Denham & Small (1971)	Yonki, New Guinea	8	-	8	U	U	M_L[1]	U	U	r_{hypo}	1	U	U	A
Davenport (1972)	Unknown	U	-	U	U	U	U	U	U	r_{hypo}	1	U	U	A
Donovan (1973)	Mostly W. USA but 100+ foreign	678	-	U	<5	>8	U	3*	450*	r_{hypo}	1	U	U	A
Denham *et al.* (1973)	Papua New Guinea	25	-	25	5.2	8.0	M_L	80*	300	U	1	U	1	A
Esteva & Villaverde (1973) & Esteva (1974)	W. USA	U	-	U	U	U	U	15*	150*	r_{hypo}	1	B	U	A
Orphal & Lahoud (1974)	California	140	-	31	4.1	7.0	M_L	15	350	r_{hypo}	1	U	O	A
Ambraseys (1975b), Ambraseys (1975a) & Ambraseys (1978a)	Europe	58	-	U[2]	3.5	5.0	M_L	5	35	r_{hypo}	1	U[3]	U	A
Trifunac & Brady (1975), Trifunac (1976) & Trifunac & Brady (1976)	W. USA	181	181	57	3.8	7.7	Mostly M_L	6[4]*	400[5]*	r_{epi}	3	B	O	A

continued on next page

[1] State that it is Richter magnitude which assume to be M_L
[2] Ambraseys & Bommer (1995) state that uses 38 earthquakes.
[3] Ambraseys & Bommer (1995) state that uses larger component.
[4] Note only valid for $R \geq 20\,\mathrm{km}$
[5] Note only valid for $R \leq 200\,\mathrm{km}$

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Blume (1977)	California & W. Nevada	795[6]	-	U	U	U	M_L	U	U	r_{hypo}	2 (1)	B	U	A
McGuire (1977)	W. USA	34	-	22	5.3	7.6	M_L	14	125	r_{hypo}	1	B	U	A
Milne (1977)	W. USA	200*	-	U	3.5	7.7	U	1	380	r_{hypo}	1	U	U	A
Ambraseys (1978b)	Europe & Middle East	162	-	U	3.0*	6.6	m_b	0*	30*	r_{hypo}	1	L	O	A
Donovan & Bornstein (1978)	W. USA	59	-	10	5.0	7.7	U[7]	0.1	321	r_E, r_{rup} and r_{hypo}	1	B	O	A
Faccioli (1978)	Mostly W. USA & Japan, some foreign	47[8]	-	23	4.9	7.8	U[9]	15	342	r_{hypo}	1	B	U	A
McGuire (1978)	W. USA	70	-	17+*	4.5*	7.7	U[10]	11*	210*	r_{hypo}	2	B	U	A
A. Patwardhan *et al.* (1978)[11]	Worldwide	63 (32)	-	25 (23)	4 (5.3)	7.7 (7.8)	M_s	U	U	r_{rup}	2	B	U	A
Cornell *et al.* (1979)	W. USA	70	-	U	U	U	M_L	U	U	r_{hypo}	1	C	U	A
Faccioli (1979)	Friuli, Italy	19[12]	-	5*	3.7	6.3	M_L	10*	30*	r_{hypo}	1	B	1	A
Faccioli & Agalbato (1979)	Friuli, Italy	66	52	14	3.7	6.3	M_L	5 (r_{epi})	190 (r_{epi})	r_{hypo}	2	B	1	A
Aptikaev & Kopnichev (1980)	Worldwide	Many 100s	- (70*)	U (59)	U	U	U	U	U	r_{hypo}	1	U	U	A (T, TS, S, SN, N)[13]
Blume (1980)	W. USA	816	-	U	2.1	7.6	U	0	449	r_{hypo}	1	B	1, O	A
Iwasaki *et al.* (1980)	Japan	301	-	51	$>$5.0	$<$7.9	M_L[14]	$<$20	$>$200	r_{epi}	4	U	1	A

continued on next page

[6]Total earthquake components (does not need to be multiplied by two) for magnitude and distance dependence. Uses 2713 underground nuclear explosion records for site dependence.

[7]Idriss (1978) finds magnitudes to be mixture of M_L and M_s.

[8]Total earthquake components (does not need to be multiplied by two)

[9]Idriss (1978) believes majority are M_s.

[10]Idriss (1978) finds magnitudes to be mixture of M_L, m_b and M_s.

[11]Reported in Idriss (1978).

[12]Does not need to be multiplied by two.

[13]Assume dip-slip means normal mechanism.

[14]State that it is Richter magnitude which assume to be M_L

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Matuschka (1980)	New Zealand	61	-	U	4.5*	U	U	U	120	d_{hypo}	U	U	1	A
Ohsaki *et al.* (1980a)	Japan	75	75	U	4	7.4	U	6	500	r_{hypo}	1	U	1	A
Campbell (1981)	W. USA+8 foreign	116	-	27	5.0	7.7	M_L for $M < 6.0$ and M_s otherwise	0.08	47.7	r_{rup}	1	M	O	A
Chiaruttini & Siro (1981)	Europe & Mid. East	224	-	117	2.7	7.8	M_L (m_b)	3	480	r_{hypo}	1	L	1	A
Joyner & Boore (1981)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	r_{jb}	2	L	2	A
Bolt & Abrahamson (1982)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	r_{jb}	1	L	O	A
Joyner & Boore (1982b) & Joyner & Boore (1988)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	r_{jb}	2	L	2	A
PML (1982)	Europe + USA + others	113	-	32	4.3	8	M_s	0.1	330	r_{hypo} or r_{rup}	1	U	U	A
Schenk (1982)	Unknown	3500	-	U	2.5	6.5	M_s	2	600	r_{hypo}	1	U	O	A
Brillinger & Preisler (1984)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	r_{jb}	2	L	1M	A
Joyner & Fumal (1984) and Joyner & Fumal (1985)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	r_{jb}	C	L	2	A
Kawashima *et al.* (1984) & Kawashima *et al.* (1986)	Japan	197	-	90	5.0	7.9	M_{JMA}	5*	550*	r_{epi}	3	R	1	A
McCann Jr. & Echezwia (1984)	N. America + foreign	83	-	18	$5.0+$	U	M_w	U	U	r_{rup}	1	U	O	A
Schenk (1984)	Unknown	3500	-	U	2.5	6.5	U	2	600	r_{hypo}	1	U	O	A
Xu *et al.* (1984)	N. China	19	-	10	4.5	7.8	M_w (M_L for $M < 6.0$, M_s for $M \geq 6.0$)	10.1	157	r_{epi}	1	L	1	A

continued on next page

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Brillinger & Preisler (1985)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	r_{jb}	2	L	1M	A
Kawashima *et al.* (1985)	Japan	-	119	90*	5.0*	7.5*	M_{JMA}	5*	500*	r_{epi}	3	-	1	A
Peng *et al.* (1985b)	N.E. China	73	-	20	3.7	7.8	M_C	2	442.5	r_{epi}	1	U	1	A
Peng *et al.* (1985a)	Tangshan region, China	93	87	19	2.9	5.3	M_L	2*	50*	r_{epi}	1	L	2	A
PML (1985)	USA + Europe + others	203	-	46	3.1	6.9	M_s	0.1	40	r_{rup}	1	U	U	A (S, T)
McCue (1986)	E. Australia	U	-	U	1.7	5.4	M_L	2.5	134	r_{hypo}	1	U	U	A
C.B. Crouse (1987)[15]	S. California	U	-	U	U	U	M_s	U	U	r_{rup}	1	B	U	A
Krinitzsky *et al.* (1987) & Krinitzsky *et al.* (1988)	Plate boundaries[16]	389[17]	-	U	5.0*	7.4*[18]	M[19]	7*[20]	200*[21]	r_{hypo}[22]	2	B	O	A
Sabetta & Pugliese (1987)	Italy	95	-	17	4.6	6.8	M_s for $M \geq 5.5$, M_L otherwise	1.5, 1.5	179, 180	Both r_{jb} & r_{epi}	2	L	1	A
K. Sadigh (1987)[23]	W. USA + others	U	-	U	U	U	M_w	U	U	r_{rup}	2	B	U	A (S, R)
Singh *et al.* (1987)	Mexico	16	-	16	5.6	8.1	M_s	282	466	r_{rup}	1	U	1	A
Algermissen *et al.* (1988)	Vicinity of San Salvador	82	-	U	U	U	M_s	U	U	r_{hypo}	1	M	U	A
Annaka & Nozawa (1988)	Japan	U	-	45	U	U	U	U	U	U	1	U	1	A

continued on next page

[15]Reported in Joyner & Boore (1988).
[16]Also derive equations for Japan subduction zones.
[17]195 for subduction zone equations.
[18]$>$7.5 for subduction zone equations.
[19]Call magnitude scale Richter magnitude, which note is equivalent to M_w for $M \leq 8.3$, M_L for $M < 5.9$ and M_s for $5.9 \leq M \leq 8.0$.
[20]About 15km for subduction zone equations.
[21]About 400km for subduction zone equations.
[22]r_{epi} for subduction zone equations.
[23]Reported in Joyner & Boore (1988).

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
K.W. Campbell (1988)[24]	Worldwide	U	-	U	$\geq$ 5	U	M_L for $M < 6.0$ and M_s otherwise	U	<50	r_{seis}	2	M	U	A (S, R)
Fukushima *et al.* (1988) & Fukushima & Tanaka (1990)	Japan+200 W. USA	486+200	-	28+15	4.6(5.0)	8.2(7.7)	M_s (M_{JMA})	16 (0.1)	303 (48)	r_{hypo}, r_{rup} for 2 Japanese & all US	4	G	2	A
Gaull (1988)	S.W. W. Australia	25+	-	12+	2.6	6.9	M_L	2.5	175	r_{hypo}	1	U	O	A
Joyner & Boore (1988)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	r_{jb}	2	L, O	2W	A
McCue *et al.* (1988)	S.E. Australia	62	-	U	0.5*	6*	M_L	5*	833	r_{epi}	1	U	O	A
Petrovski & Marcellini (1988)	Europe	120	120	46	3	7	U	8	200	r_{hypo}	1	L	1	A
Tong & Katayama (1988)	Kanto (Japan)	<227	-	<27	4.5*	7.9*	U	10*	750*	r_{epi}	C	L	O	A
Yamabe & Kanai (1988)	Japan	U	-	22	5.3	7.9	U	U	U	r_{hypo}	1	U	O	A
Youngs *et al.* (1988)	Worldwide subduction zones	197+389	-	60	5	8.1 (8.2)[25]	M_w (M_s, m_b)	15* (20*)	450* (450*)	r_{rup}, r_{hypo} for $M_w \lesssim 7.5$	1	G	1W	A (B,F)
Abrahamson & Litehiser (1989)	$75\%+$ California, rest foreign	585	585	76	5.0	8.1	M_s for $M_s \geq 6.0$, M_L (m_b) otherwise	0.08	400	r_{rup}	1	L	O	A (R & RO, I)
Campbell (1989)	W. N. America + 3 from Managua	190	-	91	2.9	5.0	M_L	0.6	18.3	r_{epi}	1	M	O	A
Ordaz *et al.* (1989)	Guerrero, Mexico	U	-	U	U	U	U	U	U	U	U	U	U	A
Alfaro *et al.* (1990)	Guatemala, Nicaragua & El Salvador	20	-	12	4.1	7.5	M_s	1	27	r_{epi}	1	L	U	A
Ambraseys (1990)	W. N. America	182	-	23	5.03	7.7	M_w (M_L)	0.5	370	r_{jb}	2	L	2	A

continued on next page

[24] Reported in Joyner & Boore (1988).
[25] Consider equations valid for $M_w \leq 8$

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Campbell (1990)	Unknown	U	-	U	U	U	M_L for $M < 6$, M_s for $M \geq 6$	U	U	r_{seis}	1	U	U	A
Dahle *et al.* (1990b) & Dahle *et al.* (1990a)	Worldwide intraplate regions	87	-	56	2.9	7.8	M_s (M_L, m_b, M_{CL})	6	1300	r_{hypo}	1	L	2	A
Jacob *et al.* (1990)	E. N. America	U	-	8	1.8	6.4	m_b	≤ 20	820	U[26]	1	U	O	A
Sen (1990)	Whittier Narrows area	72*	-	11	2.2	3.5	M_L	12*	21*	r_{hypo}	1	U	1M	A (T)
Sigbjörnsson (1990)	Iceland	U	-	U	U	5.8[27]	U	U	U	r_{jb}	1	U	U	A
Tsai *et al.* (1990)	Worldwide	<217	-	<51	4.9*	7.4	M_w	3*	150*	r_{rup}	1	M	U	T (S,O)
Ambraseys & Bommer (1991) & Ambraseys & Bommer (1992)	Europe & Mid. East	529	459	H:219, V:191	4	7.34	M_s	1	H:313, V:214	r_{jb} for $M_s \gtrsim 6.0$, r_{epi} otherwise	1	L	1, 2	A
Crouse (1991)	Worldwide subduction zones	697[28]	-	U	4.8	8.2	M_w (M_s, M_{JMA})	>8	>866	r_E, r_{hypo} for $M < 7.5$	1	B	1	A
Garcìa-Fernàndez & Canas (1991) & Garcia-Fernandez & Canas (1995)	Iberia[29]	57	367	U	3.1	5.0	m_{bLg}	U	U	r_{epi}	1	-	1	A
Geomatrix Consultants (1991), Sadigh *et al.* (1993) & Sadigh *et al.* (1997)	California with 4 foreign	960+4	U	119+2	3.8 (6.8)	7.4 (7.4)	M_w	0.1 (3)	305 (172)[30]	r_{rup} for some, r_{hypo} for small ones	2	G	U	A(R,S)

continued on next page

[26] Free (1996) believes it is r_{hypo}.
[27] This is M_s.
[28] Total number of components, does not need to be multiplied by two.
[29] Also present equations for SSE (using 140 records) and NE Iberia (using 107 records).
[30] Equations stated to be for distances up to $100\,\mathrm{km}$

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Huo & Hu (1991)	W. USA with 25 foreign	383+25	-	14+2	5.0	7.4 (7.3)	M_L or m_b for $M < 6.0$ and M_s otherwise	0.1	227 (265)	r_{jb}	2	B	O	A
I.M. Idriss (1991) reported in Idriss (1993)	Unknown	572	-	30*	4.6	7.4	M_L for $M < 6$, M_s for $M \geq 6$	1	100	r_{rup}, r_{hypo} for $M < 6$	1	U	U	A
Loh *et al.* (1991)	Taiwan	112	-	63	4.0	7.1	M_L	5.0	178.3	r_{hypo}	1	L	U	A
Matuschka & Davis (1991)	New Zealand	80	80	30	U	U	U	U	U	U	3	B	U	A
Niazi & Bozorgnia (1991)	SMART-1 array, Taiwan	236	234	12	3.6	7.8	M_L (M_D) for $M_L < 6.6$, else M_s	3.1[31]	119.7[31]	r_{hypo}	1	M	2W	A
Rogers *et al.* (1991)	Worldwide	1241	-	180*	5.3*	8.1*	M_L for $M \leq 6$, M_s for $6 < M < 8$ and M_w for $M \geq 8$	4*	400*	r_{rup} if have, r_{hypo} otherwise	6	L	1	A
Stamatovska & Petrovski (1991)	Mainly Italy and former Yugoslavia	489[32]	-	78	3*	8*	M_L	10*	500*	r_{hypo}	1	B	1	A
Abrahamson & Youngs (1992)	Unknown	U	-	U	U	U	U	U	U	U	1	U	1M	A (U, U)
Ambraseys *et al.* (1992)	USA + Europe + others	504	-	45	3.1	6.87	M_s	0.5	39	r_{jb}, r_{epi} for some	1	L	1	A
Kamiyama *et al.* (1992) & Kamiyama (1995)	Japan	357	-	82	4.1	7.9	M_{JMA}	3.4	413.3	r_{hypo}	I	B	O	A
Sigbjörnsson & Baldvinsson (1992)	Iceland	262	-	39	2.0	6.0	U	2	80	r_{jb}	2	B,L	2	A

continued on next page

[31] Distance to centre of array

[32] Does not need to be multiplied by two.

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Silva & Abrahamson (1992)	W. USA with 4 foreign	136	-	12	6.1	7.4	M_w	3*	100*	r_{seis}	2	G	1M	A (S,R)
Taylor Castillo *et al.* (1992)	Nicaragua, El Salvador & Costa Rica	89	-	27	3.0	7.6	M_s	6	210	r_{hypo}	1	L	U	A
Tento *et al.* (1992)	Italy	137	-	40	4	6.6	M_L	3.2	170	r_{jb} for $M_L \geq 5.7$, r_{epi} otherwise	1	L	2	A
Theodulidis & Papazachos (1992)	Greece+16 foreign	105+16[33]	-	36+4	4.5 (7.2)	7.0 (7.5)	M_s, M_w, M_{JMA}	1 (48)	128 (236)	r_{epi}	2	B	O	A
Abrahamson & Silva (1993)	W. USA with 4 foreign	201	-	18	6.0	7.4	M_w	0.6*	100*	r_{rup}	2	G	1M	A (S, R)
Boore *et al.* (1993), Boore *et al.* (1997) & Boore (2005)	W. N. America	271	-	20	5.1[34]	7.7	M_w	0	118.2	r_{jb}	3	L, G	2M	A
Campbell (1993)	Worldwide	U	-	U	U[35]	U	M_L for $M < 6.0$ and M_s otherwise	U	U[36]	r_{seis}	2	M	O	A (T,S)
Dowrick & Sritharan (1993)	New Zealand	U	-	8	U	U	U	U	U	r_{jb}	U	U	1	A
Gitterman *et al.* (1993)	Israel	U	-	U	3.9	5.1	M_L	U	U	r_{epi}	1	U	U	A
McVerry *et al.* (1993) & McVerry *et al.* (1995)	New Zealand	256	-	31*	5.1	7.3	M_w	13	312	r_c or r_{hypo}	1	L	1	A, R
Singh *et al.* (1993)	Nicaragua, El Salvador & Costa Rica	89	-	27	3.0	7.6	M_s	6	210	r_{hypo}	1	V	O	A

continued on next page

[33] Total number of components does not need to be multiplied by two

[34] Boore *et al.* (1997) revise this magnitude to 5.87. New minimum magnitude is 5.2.

[35] Considers equation valid for $M \geq 4.7$.

[36] Considers equation valid for $d \leq 300\,\mathrm{km}$.

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Steinberg *et al.* (1993)	Worldwide	U	-	U	U	5*	U	U	U	r_{epi}	1	U	1	A
Sun & Peng (1993)	W. USA with 1 foreign	150+1	-	42+1	4.1	7.7	M_L for $M < 6$, else M_s	2*	150*	r_{epi}	C	R	1	A
Ambraseys & Srbulov (1994)	Worldwide	947	-	76	5.0	7.7	M_s	1	375	r_{jb}, r_{epi}	1	L	2W	A
Boore *et al.* (1994a) & Boore *et al.* (1997)	W. N. America	271 (70)	-	20 (9)	5.1[37] (5.3)	7.7 (7.4)	M_w	0	118.2 (109)	r_{jb}	C	L, G	1M, 2M	A (R,S)[38]
El Hassan (1994)	Unknown	U	-	U	U	U	M_L	U	U	r_{hypo}	1	U	1	A
Fukushima *et al.* (1994) & Fukushima *et al.* (1995)	3 vertical arrays in Japan	285	284	42	5.0	7.7	M_{JMA}	60*	400*	r_{hypo}	I	B	1,2	A
Lawson & Krawinkler (1994)	W. USA	250+	-	11	5.8	7.4	M_w	U	100	r_{jb}	3	U	1M	A
Lungu *et al.* (1994)	Romania	≈ 300	125	4	6.3	7.4	M_w	U	U	r_{hypo}	1	U	1	A
Musson *et al.* (1994)	UK + 30* foreign	15 + 30*	-	4+16	3 (3.7)	3.5 (6.4)	M_L	70* (>1.3)	>477.4 (200*)	r_{hypo}	1	U[39]	O	A
Radu *et al.* (1994), Lungu *et al.* (1995a) & Lungu *et al.* (1996)	Romania	106	-	3	6.7(M_L) or 7.0(M_w)	7.2(M_L) or 7.5(M_w)	U[40]	90*	320*	r_{hypo}	1	L	1	A
Ramazi & Schenk (1994)	Iran	83	83	20	5.1	7.7	M_s[41]	≤ 8	≥ 180	r_{hypo} for most, r_{rup} for 19[42]	2	U	U	A
Xiang & Gao (1994)	Yunnan, China + 114 W. N. America	131+114	-	U	2.5*	7.6*	M_s (M_L)	2*	120*	r_{epi}	1	L	U	A
Aman *et al.* (1995)	Himalayan region	84*	-	5	5.7	7.2	M_B	3*	350*	r_{epi}	1	U	U	A

continued on next page

[37] Boore *et al.* (1997) revise this magnitude to 5.87. New minimum magnitude is 5.2.
[38] Coefficients given in Boore *et al.* (1994b)
[39] Free (1996) believes it is largest horizontal component.
[40] It is not clear whether use Richter magnitude (M_L) or M_w.
[41] Some may be m_b because in their Table 1 some earthquakes to not have M_s given but do have m_b. If so new minimum is 5.0.
[42] They state it is 'closest distance from the exposure of ruptured part of the fault, instead of focal distances' so may not be rupture distance.

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Ambraseys (1995)	Europe and Mid. East	830	620	334	4.0	7.3	M_s	0*	260*	r_{jb} for $M_s > 6.0$, r_{epi} otherwise	1	L	2W	A
Dahle *et al.* (1995)	Cen. America	280	-	72	3*	8*	M_w (M_s, m_b,M_D)	6*	490*	r_{hypo}	2	L	1B	A
Lee *et al.* (1995)	W. N. America	1926	1926	297	1.7	7.7	Usually M_L for $M \leq 6.5$ and M_s for $M > 6.5$	2	200+	r_{hypo}	9, 3 $\times$ C	U	1	A
Lungu *et al.* (1995b)	Romania	106	-	3	6.7(M_L) or 7.0(M_w)	7.2(M_L) or 7.5(M_w)	U[43]	U	U	r_{hypo}	1	L	1	A
Molas & Yamazaki (1995)	Japan	2166	-	387	4.1*	7.8*	M_{JMA}	8*	1000*	r_{rup} for 2 earthquakes, r_{hypo} otherwise	I	L	O	A
Sarma & Free (1995)	E. N. America[44]	77	-	33	2.8	5.9	M_w (m_b, M_L, M_s)	0	820	r_{jb} or r_{epi}	2	U	1	A
Ambraseys *et al.* (1996) & Simpson (1996)	Europe & Mid. East	422	-	157	4.0	7.9	M_s (unspecified)	0	260	r_{jb} for $M_s > 6.0$, r_{epi} otherwise	3	L	2W[45]	A
Ambraseys & Simpson (1996) & Simpson (1996)	Europe & Mid. East	-	417	157	4.0	7.9	M_s (unspecified)	0	260	r_{jb} for $M > 6.0$, r_{epi} otherwise	3	-	2W[46]	A
Aydan *et al.* (1996)	Turkey	27*	23*	19*	3.5*	7.6*	M_s	10*	350*	r_{hypo}	1	U	1	A

continued on next page

[43] It is not clear whether use Richter magnitude (M_L) or M_w.

[44] Also derive equations for Australia and N. E. China

[45] Ambraseys *et al.* (1996) state it is two-stage of Joyner & Boore (1981) but in fact it is two-stage method of Joyner & Boore (1988).

[46] Ambraseys *et al.* (1996) state it is two-stage of Joyner & Boore (1981) but in fact it is two-stage method of Joyner & Boore (1988).

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Bommer *et al.* (1996)	El Salvador & Nicaragua	36	-	20	3.7	7.0	M_s	62	260	r_{hypo}	1	L	U	A
Crouse & McGuire (1996)	Cen. & S. California	238	-	16	6.0	7.7	M_s	0.1	211	r_{rup}	4	G	1W	R,S (R,S)
Free (1996) & Free *et al.* (1998)	Stable continental regions	558	478	H: 222, V: 189	1.5	6.8	M_w	0	820	r_{jb} for some, r_{epi} for most	2	L	1	A
Inan *et al.* (1996)	Turkey	U	-	U	U	U	U	U	U	r_{epi}	1	U	U	A
Ohno *et al.* (1996)	California	248	-	17	5.0	7.5	M_w (M_L)	7.2	99.6	r_q for $M > 5.3$, r_{hypo} otherwise	2	B	2M	A
Romeo *et al.* (1996)	Italy	95	-	17	4.6*	6.8*	M_w	1.5, 1.5	179, 180	Both r_{jb} & r_{epi}	2	L	1	A
Sarma & Srbulov (1996)	Worldwide	350	-	114	3.9	7.7	M_s	1	213	r_{jb} & r_{epi}	1	B, L	U	A
Singh *et al.* (1996)	Himalayas	86	-	5	5.7	7.2	m_b	33.15	340.97	r_{hypo}	1	U	1	A
Spudich *et al.* (1996) & Spudich *et al.* (1997)	Worldwide extensional regimes	128	-	30	5.10	6.90	M_w	0	102.1	r_{jb}	2	G, O	2M	NS
Stamatovska & Petrovski (1996)	Romania, Bulgaria & former Yugoslavia	190[47]	-	4	6.1	7.2	M_L[48]	10*	310*	r_{epi}	1	B	1	A
Campbell (1997), Campbell (2000), Campbell (2001) & Campbell & Bozorgnia (1994)	Worldwide	645	225	H:47, V:26	4.7	H:8.0, V:8.1	M_w	3	60	r_{seis}	3	G	1	A(S,R,N)
Munson & Thurber (1997)	Hawaii	51	-	22	4.0	7.2	M_s for $M_s \geq 6.1$, M_L otherwise	0	88	r_{jb}	2	L	2M	A

continued on next page

[47] Total number of components. Does not need to be multiplied by two.
[48] Called Richter magnitude.

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Pancha & Taber (1997)	New Zealand	U	-	U	U	U	U	U	U	U	1	U	2	A
Rhoades (1997)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	r_{jb}	1	L	O	A
Schmidt *et al.* (1997)	Costa Rica	200	-	57	3.3	7.6	M_w (M_s, m_b, M_D)	6.1	182.1	r_{hypo}	3	L, B	O	A
Youngs *et al.* (1997)	Worldwide subduction zones	476	-	164	5.0	8.2	M_w (M_s,m_b)	8.5	550.9	r_{rup}, r_{hypo} for some	2	G	1M	NT
Zhao *et al.* (1997)	NZ with 66 foreign	461[49]+66	-	49+17	5.08	7.23(7.41)	M_w	11 (0.1)	573 (10)	r_{rup} for some, r_c for most	2	U	1	A(R)
Baag *et al.* (1998)	Korea	U	-	U	U	U	U	U	U	r_{epi}	1	U	U	A
Bouhadad *et al.* (1998)	Algeria	U	-	2	5.6	6.1	M_s	20	70	r_{hypo}	1	L, M	1	A
Costa *et al.* (1998)	Friuli	80*	80*	20*	1.3*	4.3*	M_D	3*	66*	r_{hypo}	1	U	1	A
Manic (1998)	N.W. Balkans	276[50]	-	56	4	7	M_s	U	U	r_{hypo}	2	B	1	A
Reyes (1998)	University City, Mexico City	20+	-	20+	U	U	M_w	U	U	r_{rup}	I	S	U	A
Rinaldis *et al.* (1998)	Italy & Greece	137*	-	24*	4.5	7	M_s or M_w	7	138	r_{epi}	2	U	O	A (N,ST)
Sadigh & Egan (1998)	California with 4 foreign	960+4	-	119+2	3.8	7.4	M_w	0.1	305[51]	r_{rup} for some, r_{hypo} for small ones	2	G	U	A(R,SN)
Sarma & Srbulov (1998)	Worldwide	690[52]	-	113	3.9	7.7	M_s (U)	0	197	r_{jb}, r_{epi}	2	B	1	A
Sharma (1998)	Indian Himalayas	66	-	5	5.5	6.6	U	8	248	r_{hypo}	1	L	1W	A
Smit (1998)	Switzerland + some from S. Germany	$\ll$ 1546	$<$1546	H: $<$120, V: 120	2.0	5.1	M_L	1	290	r_{hypo}	1	U	2	A

continued on next page

[49] Includes some not used for regression
[50] Total number of components do not need to be multiplied by two.
[51] Equations stated to be for distances up to $100\,\mathrm{km}$
[52] Total number of components do not need to be multiplied by two.

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Cabañas *et al.* (1999), Cabañas *et al.* (2000) & Benito *et al.* (2000)	Mediterranean region[53]	U	U	U	2.5	7.0	M_s[54]	0	250	r_{epi}[55]	4	L	1	A
Chapman (1999)	W. N. America	304	-	23	5.0	7.7	M_w	0.1	189.4	r_{jb}	3	G	2M	A
Cousins *et al.* (1999)	NZ with 66 foreign	610+66	-	25+17	5.17	7.09(7.41)	M_w	0.1	400	r_{rup} for some, r_c for most	3	U	U	A(R)
Ólafsson & Sigbjörnsson (1999)	Iceland	88[56]	-	17	3.4	5.9	M_w[57]	2	112	r_{epi}	1	B	1	A
Spudich *et al.* (1999)	Worldwide extensional regimes	142	-	39	5.1	7.2	M_w	0	99.4	r_{jb}	2	G, O	1M	NS
Wang *et al.* (1999)	Tangshan, N. China	44	-	6	3.7	4.9	M_s (M_L)	2.1	41.3	r_{epi}	1	L	1	A
Zaré *et al.* (1999)	Iran	468	468	47*	2.7	7.4	M_w (M_s, m_b, M_L)	4	224	r_{hypo} (r_{rup} for 2)	4	B	2M	R, RS & S
Ambraseys & Douglas (2000), Douglas (2001b) & Ambraseys & Douglas (2003)	Worldwide	186	183	44	5.83	7.8	M_s	0	15	r_{jb}	3	L	1	A
Bozorgnia *et al.* (2000)	Worldwide	2823	2823	48	4.7	7.7	M_w	U	≤ 60	r_{seis}	4	G	U	A (R,S,T)
Campbell & Bozorgnia (2000)	Worldwide	960[58]	941[59]	49[60]	4.7	7.7	M_w	1*	60*	r_{seis}	4	G	1	A (S,R,T)
Field (2000)	S California	447	-	28	5.1	7.5	M_w	0	148.9	r_{jb}	C (6)	G	1M	A (R, S, O)

continued on next page

[53] Also derive equations for Spain.
[54] Also derive equations using M_L.
[55] Also derive equations using r_{hypo}.
[56] Total number of components. Does not need to be multiplied by two.
[57] Equation given in terms of $\log M_0$.
[58] Equation for corrected PGA uses 443 records.
[59] Equation for corrected PGA uses 439 records.
[60] Equation for corrected PGA uses data from 36 earthquakes.

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Jain *et al.* (2000)	Central Himalayas	32 (117)	-	3	5.5	7.0	U	2 (4)	152 (322)	r_{epi}	1	U	1	T
Kobayashi *et al.* (2000)	Japan	U	-	U	5.0	7.8	M_w	0.9*	400*	U	4	B	1M	A
Monguilner *et al.* (2000a)	W. Argentina	54[61]	-	10[61]	4.3[61]	7.4	M_s if M_L & $M_s > 6$, M_L otherwise	11[61]	350[61]	r_{hypo}	2	U	1W	A
Sharma (2000)	Indian Himalayas	-	66	5	5.5	6.6	U	8	248	r_{hypo}	1	-	1W	A
Si & Midorikawa (1999, 2000)	Japan	856	-	21	5.8	8.3	M_w	0*	280*	Both r_q & r_{rup}	2	L	O	A
Smit *et al.* (2000)	Caucasus	84	-	26	4.0	7.1	M_s	4	230	r_{epi}[62]	1	L	2	A
Takahashi *et al.* (2000)	Japan+166 foreign	1332	-	U+7*	5* (5.8*)	8.3* (8*)	M_w	1* (0.1*)	300* (100*)	r_{rup}, r_{hypo} for some	4	G	O	A
Wang & Tao (2000)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	r_{jb}	2	L	O	A
Chang *et al.* (2001)	Taiwan	4720[63], 2528[64]	-	45[63], 19[64]	4.1[63], 4.6[64]	7.0[63], 6.3[64]	M_w (M_L for $M_L < 6.5$)	0[63], 40.2[64]	264.4[63], 272.4[64]	r_{epi}[63], r_{hypo}[64]	1	G	2	A
Herak *et al.* (2001)	Dinarides	145	145	46	4.5	6.8	M_L	3*	200*	r_{epi}	1	L	2	A
Lussou *et al.* (2001)	Japan	3011	3011	102	3.7	6.3	M_{JMA}	4*	600*	r_{hypo}	4	B	2	A
Sanchez & Jara (2001)	Pacific coast of Mexico	U	-	U	U	U	M_s	U	U	r_{epi}	1	U	U	BF
Wu *et al.* (2001)	Taiwan	1941	-	60	4.8	7.6	M_w (M_L)	0.05*	400*	r_{rup} (r_{epi} for some)	1 & I	U	U	A
Chen & Tsai (2002)	Taiwan	424	-	48	U	U	M_L	U	U	r_{hypo}	1	U	O	A
Gregor *et al.* (2002a)	Shallow crustal worldwide (mainly California)	993	993	68	4.4	7.4	M_w	0.1	267.3	r_{rup}	2	U	1M	A (S, R/O, T)

continued on next page

[61] Assuming they use same data as Monguilner *et al.* (2000b).
[62] Smit *et al.* (2000) give r_{hypo} but this is typographical error (Smit, 2000).
[63] Shallow crustal records.
[64] Subduction records.

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Gülkan & Kalkan (2002)	Turkey	93[65]	-	19	4.5	7.4	M_w	1.20	150	r_{jb}, r_{epi}	3	L, R	1	A
Khademi (2002)	Iran	160	160	28*	3.4*	7.4	M_w (m_b for $M_s < 5$ and M_s otherwise)	0.1*	180*	r_{jb}, r_{epi} for $M < 5.9$	2	L	O	A
Margaris *et al.* (2002a) & Margaris *et al.* (2002b)	Greece	744	-	142	4.5	7.0	M_w	1	150	r_{epi}	3	B	O	A
Saini *et al.* (2002)	Indian Himalayas	U	U	U	U	U	U	U	U	U	U	U	U	A
Schwarz *et al.* (2002)	N.W. Turkey	683	683	U	0.9*	7.2	M_L	0*	250*	r_{epi}	3	U	1	A
Stamatovska (2002)	Romania	190[66]	-	4	6.1	7.2	U	10*	310*	r_{epi}	1	B	1	A
Tromans & Bommer (2002)	Europe	249	-	51	5.5	7.9	M_s	1	359	r_{jb}	3	L	2	A
Zonno & Montaldo (2002)	Umbria-Marche	161	-	15	4.5	5.9	M_L	2*	100*	r_{epi}	2	L	2	N, O
Alarcón (2003)	Colombia	47	-	U	4.0	6.7	M_s	49.7	322.4	r_{hypo}	1	U	U	A
Alchalbi *et al.* (2003)	Syria	49	49	10	3.5	5.8	M_{CL}	21	400	r_{hypo}	2	U	1	A
Atkinson & Boore (2003)	Subduction zones	1200+	-	43*	5.5	8.3	M_w	11*	550*	r_{rup}	4	C	1M	F, B
Boatwright *et al.* (2003)	N. California	4028	-	104	3.3	7.1	Mainly M_w, M_L for some	1*	370*	r_{hypo}	4	U	O	A
Bommer *et al.* (2003)	Europe & Mid. East	422	-	157	4.0	7.9	M_s (unspecified)	0	260	r_{jb} for $M_s > 6.0$, r_{epi} otherwise	3	L	1M	A (S, R, N)

continued on next page

[65] This is total number of horizontal components used. They come from 47 triaxial records.
[66] This is total number of components. Does not need to be multiplied by two.

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Campbell & Bozorgnia (2003d), Campbell & Bozorgnia (2003a) & Bozorgnia & Campbell (2004b)	Worldwide	443[67]	439[68]	36[69]	4.7	7.7	M_w	2*	60*	r_{seis}	4	G	1	A (S & N, R, T)
Halldórsson & Sveinsson (2003)	Iceland	131	-	12	4.1	6.6	M_{Lw}	5*	300*	U	1	U	1	A
Shi & Shen (2003)	Shanghai region	U	-	U	U	U	M_s	U	U	r_{hypo}	1	U	U	A
Sigbjörnsson & Ambraseys (2003)	Europe & Middle East	465	-	U	5*	7*	M_w or M_s	1*	500*	r_{jb} if available, r_{epi} otherwise	1	L	1	S
Skarlatoudis *et al.* (2003)	Greece	1000	-	225	4.5	7.0	M_w (M_L)	1.5*	150*	r_{epi}	2	U	O	A (N, ST)
Beauducel *et al.* (2004)	Guadeloupe	1430	-	398	1.1	6.3	M_D (m_b, M_w)	1.7	450	r_{hypo}	1	R	1	A
Beyaz (2004)	Unknown (Turkey?)	U	-	U	U	U	M_w	U	U	r_{epi}	1	U	1	A
Bragato (2004)	NE Italy (45–46.5°N & 12–14°E)	814	-	192	2.5	4.5	M_L	U	U	r_{epi}	1	U	O	A
Gupta & Gupta (2004)	Koyna region, India	31	31	U	U	6.5	M_L	3*	25*	r_{hypo}	1	L	O	A
Kalkan & Gülkan (2004a)	Turkey	-	100	47	4.2	7.4	M_w (unspecified scales)	1.2	250	r_{jb}, r_{epi} for small events	3	-	1	A
Kalkan & Gülkan (2004b) and Kalkan & Gülkan (2005)	Turkey	112	-	57	4.0	7.4	M_w (unspecified scales)	1.2	250	r_{jb}, r_{epi} for small events	3	L[70]	1	A

continued on next page

[67]There are 960 components for uncorrected PGA.
[68]There are 941 components for uncorrected PGA.
[69]For horizontal corrected records. There are 49 for horizontal uncorrected PGA. There are 34 for vertical corrected records and 46 for vertical uncorrected PGA.
[70]The caption of their Table 2 states that reported coefficients are for mean.

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Lubkowski *et al.* (2004)	Stable continental regions	163	-	U	3.0	6.8	M_w (M_L)	0	854	r_{epi} (r_{jb} for 1 event)	1	U	1, 1M, 2, 2M	A
Marin *et al.* (2004)	France	63	-	14	2.6	5.6	M_L	5	700	r_{hypo}	1	L	1	A
Midorikawa & Ohtake (2004)	Japan	3335	-	33	5.5	8.3	M_w	0*	300*	r_{rup}	2	L	1	A (C, B, F)
Özbey *et al.* (2004)	NW Turkey	195	-	17	5.0	7.4	M_w (M_L)	5*	300*	r_{jb}	3	G	1M	NS
Pankow & Pechmann (2004) and Pankow & Pechmann (2006)	Worldwide extensional regimes	142	-	39	5.1	7.2	M_w	0	99.4	r_{jb}	2	G, O	1M	NS
Sunuwar *et al.* (2004)	Okhotsk-Amur plate boundary	667	667	42	4.0	5.6	M_{JMA}	$>$3	$>$264	r_{hypo}	1	L	2M	A
Skarlatoudis *et al.* (2004)	Greece	819	-	423	1.7	5.1	M_w	3	40	r_{epi}	1	U	O	A
Ulusay *et al.* (2004)	Turkey	221	-	122	4.1	7.5	M_w (M_s, m_b, M_d, M_L)	5.1	99.7	r_{epi}	3	L	1	A
Ambraseys *et al.* (2005a)	Europe & Middle East	595	-	135	5.0	7.6	M_w	0	99	r_{jb} (r_{epi} for small events)	3	L	1WM	A (N, T, S, O)
Ambraseys *et al.* (2005b)	Europe & Middle East	-	595	135	5.0	7.6	M_w	0	99	r_{jb} (r_{epi} for small events)	3	-	1WM	A (N, T, S, O)
Bragato (2005)	Worldwide	243	-	60*	5.0	7.8	M_s	0	15	r_{jb}	1	L	O	A
Bragato & Slejko (2005)	E Alps (45.6–$46.8°$N & 12–$14°$E)	1402	3168	240	2.5	6.3	M_L	0	130	r_{jb} & r_{epi}	1	R	O	A
Frisenda *et al.* (2005)	NW Italy	6899[71]	-	$>$1152	0.0*	5.1[72]	M_L	0	300[73]	r_{hypo}	2	B	1	A

continued on next page

[71] Authors state in text that 'more than 14 000' values were used but their Table 1 gives 2×6899.
[72] State equations valid to 4.5.
[73] State equations valid up to $200\,\mathrm{km}$.

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
García *et al.* (2005)	Central Mexico	277	277	16	5.2	7.4	M_w	4*	400*	r_{rup} for $M_w > 6.5$, r_{hypo} otherwise	1	G[74]	1M	B
Liu & Tsai (2005)	Taiwan	7907	7907	51	4.05	7.10	M_w (M_L)	5*	300*	r_{hypo}	1	M	2M	A
McGarr & Fletcher (2005)	Central Utah coal-mining areas	72	-	12	0.98	4.2	M_w (M_{CL})	0.5*	10*	r_{hypo}	2	L	2M	M
Nowroozi (2005)	Iran	279	279	45	3.0*	7.4	M_w (M_s, m_b, M_L)	2	245	r_{epi}	4	V	1	A
Ruiz & Saragoni (2005)[75]	Chile	41	41	8	6.4	7.8	M_s	35.72	315.01	r_{hypo}	1	B	1	F
Takahashi *et al.* (2005), Zhao *et al.* (2006) and Fukushima *et al.* (2006)	Japan+208 overseas	4518+208	-	249+20	5.0	8.3	M_w	0*	300*	r_{rup}	5	G	1M	C (R, S/N) & F, B
Wald *et al.* (2005)	California	U	-	U	U	5.3*	M_w	U	U	r_{jb}	1	L	U	A
Atkinson (2006)	Los Angeles region	4179	-	485+	3.1*	7.1*	M_w	5*	300*	r_{epi} (r_{jb} for some)	I, C	B	1	A
Beyer & Bommer (2006)	Shallow crustal (USA, Taiwan, Turkey and others)	949	-	103	4.3*	7.9*	M_w	6*	200*	r_{hypo}	U	1, 2, A, B, C, D50, G, I50, L, N, P, R	1M	A (U)
Bindi *et al.* (2006)	Umbria-Marche	239	-	45	4.0	5.9	M_L	1*	100*	r_{epi} & r_{hypo}	4	L	1M	NS

continued on next page

[74] Call it 'quadratic mean', which is assumed to be geometric mean.
[75] Also develop equations for hard rock sites and intraslab events.

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Campbell & Bozorgnia (2006a) and Campbell & Bozorgnia (2006b)	Worldwide	1500+	-	60+	4.2	7.9	M_w	0	200	r_{rup}	C	G	2M	A (R, S, N)
Costa *et al.* (2006)	NE Italy & Slovenia	900*	900*	123	3.0*	6.5*	U	1*	100*	r_{epi}	2	L, V	1	A
Gómez-Soberón *et al.* (2006)	Mexico	1983	-	109	4.5*	8.1*	M_w (M_s if $M > 6$, m_b if $M < 6$)	5*	800*	r_{hypo} (r_{rup} for some)	1	U	2	F
Hernandez *et al.* (2006)	Haulien LSTT (Taiwan)	456	456	51	5	7.3	M_L	13.7	134.8	r_{hypo}	5	B	1	A
Kanno *et al.* (2006)	Japan+some foreign	3392+377 (shallow) & 8150 (deep)	-	73+10 & 111	5.0* (6.1) & 5.5*	8.2* (7.4) & 8.0*	M_w (M_{JMA})	1* (1.5*) & 30*	450* (350*) & 450*	r_{rup} (r_{hypo} for some)	C	R	2M	A
Laouami *et al.* (2006)	Algeria	28	-	4	5.6	6.0	M_s	13	70	r_{epi} & r_{hypo}	1	U	1	A
Luzi *et al.* (2006)	Molise (Italy)	886	-	U	2.6*	5.7	M_L	5*	55*	r_{hypo}	2	L	1M	A
Mahdavian (2006)	Central Iran[76]	150	150	U	3.1	7.4	M_s (m_b)	4	98	r_{hypo}	2	A	1	A
McVerry *et al.* (2006)	New Zealand+66 overseas	535+66	-	49+17	5.08 (5.2)	7.23 (7.4)	M_w	6 (0.1)	400 (10)	r_c (r_{rup})	3	L, G	1M	C (R, OR, S & N) & F, B
Moss & Der Kiureghian (2006)	W. N. America	271	-	20	5.2	7.7	M_w	0	118.2	r_{jb}	C	G	O	A
Pousse *et al.* (2006)	Japan	9390[77]	-	U	4.1	7.3	(M_w)	5*	250*	r_{hypo} (r_{rup} for some)	5	B	2M	A
Souriau (2006)	France	175	-	20	3.0	5.4	M_L (Re-Nass & LDG)	10*	800*	r_{hypo}	1	L	1	A
Zare & Sabzali (2006)	Iran	89	89	55*	2.7	7.4	M_w	4	167	r_{hypo}	4	U	1M & 2M	A

continued on next page

[76] Also develops equations for Zagros using 98 records from an unknown number of earthquakes.
[77] Does not need to be multiplied by two.

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Akkar & Bommer (2007b)	Europe & Middle East	532	-	131	5.0	7.6	M_w	0	99	r_{jb}	3	G	1WM	A (N, S, R)
Ghodrati Amiri *et al.* (2007a) & Ghodrati Amiri *et al.* (2007b)	Alborz and central Iran[78]	200*	200*	50*	4.5*	7.3*	M_s (m_b)	5*	400*	r_{hypo}	2	L	1	A
Aydan (2007)	Turkey	U	-	U	U	U	U	U	U	r_{hypo}	C	U	U	A
Bindi *et al.* (2007)	NW Turkey	4047	4047	528	0.5	5.9	M_L[79]	5*	200*	r_{hypo}[80]	2	L	1M	A
Bommer *et al.* (2007)	Europe and Middle East	997	-	289	3	7.6	M_w	0	99	r_{jb} (r_{epi} for small events)	3	G	1WM	A (N, S, R)
Boore & Atkinson (2007) & Boore & Atkinson (2008)	Worldwide shallow crustal	1574	-	58	4.27[81]	7.90[82]	M_w	0	280[83]	r_{jb}	C	I50	2M	A (N, R, S, U)
Campbell & Bozorgnia (2007), Campbell & Bozorgnia (2008b) & Campbell & Bozorgnia (2008a)	Worldwide shallow crustal	1561	-	64	4.27[84]	7.90[85]	M_w	0.07	199.27	r_{rup}	C	I50	1M	A (N, R, S, HW)
Danciu & Tselentis (2007a) & Danciu & Tselentis (2007b)	Greece	335	-	151	4.5	6.9	M_w	0*	136	r_{epi}	3	A	1M	A (ST, N)
Douglas (2007)		See text					M_w	See text		r_{jb}	See text		1	A
Hong & Goda (2007) & Goda & Hong (2008)	California	592	-	39	5*	7.3*	M_w	0.2*	100*	r_{jb}	C	G, Q, R	1M	A

continued on next page

[78] Also develop models for the Zagros region of Iran using about 100 records.
[79] Also derive model using M_w.
[80] Also derive model using r_{epi}.
[81] Recommend that model is not extrapolated below 5 due to lack of data.
[82] Believe that model can be used to 8.0.
[83] Recommend that model is not used for distances $\geq 200\,\mathrm{km}$.
[84] Believe that model can be extrapolated down to 4.0.
[85] Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Graizer & Kalkan (2007) & Graizer & Kalkan (2008)	Worldwide shallow crustal	2583	-	47	4.9[86]	7.9[87]	M_w	0.1	349.6[88]	r_{rup}	C	U	O	A (R,SN)
Massa *et al.* (2007)	Central northern Italy	1063	-	243	2.5	5.2	M_L	0*	300*	r_{hypo}	2	L	1	A
Popescu *et al.* (2007)	Romania	U	-	58	4*	7.1	M_w	$\leq$ 70	$\geq$ 227	r_{epi}, r_{hypo}	C	L	O	A
Sobhaninejad *et al.* (2007)	Europe & Middle East	589	589	131	5.0	7.6	M_w	0	99	r_{jb} (r_{epi} for small events)	3	L	O	A (N, T, S, O)
Tavakoli & Pezeshk (2007)	Taiwan	424	-	48	4.3*	7.3*	M_L	5*	260*	r_{hypo}	1	G	O	A
Tejeda-Jácome & Chávez-García (2007)	Colima, Mexico	162	162	26	3.3	5.2	M_L	5*	175	r_{hypo}	1	G	2M	A
Abrahamson & Silva (2008) & Abrahamson & Silva (2009)	Worldwide shallow crustal	2754	-	135	4.27[89]	7.9[90]	M_w	0.06*	200*	r_{rup}	C	I50	1M	A (N, R, S, HW)
Ágústsson *et al.* (2008)	South Iceland	1085	1085	64	3.5	6.5	M_{Lw}	3*	350*	r_{epi}	1	V3	1	A
Aghabarati & Tehranizadeh (2008)	Worldwide shallow crustal	646	-	54	5.2	7.9	M_w	0	60	r_{rup}[91]	C	G	1M	A (N, R, S)
Cauzzi & Faccioli (2008), Cauzzi (2008) & Cauzzi *et al.* (2008)	Worldwide shallow crustal	1164	1132	60	5.0	7.2	M_w	6*	150*	r_{hypo}	4 & C	G	2M	A (N, R, S)

continued on next page

[86] Graizer & Kalkan (2007) state that valid down to 4.5.
[87] Graizer & Kalkan (2007) state that valid up to 7.6.
[88] Graizer & Kalkan (2007) state that valid up to $200\,\mathrm{km}$.
[89] Recommend that model is not extrapolated below 5 due to lack of data.
[90] Believe that model can be reliably extrapolated to 8.5.
[91] Not clear from article if the authors mean r_{rup} or r_{jb}.

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Chiou & Youngs (2008)	Worldwide shallow crustal	1950	-	125	4.265[92]	7.90[93]	M_w	0.2*[94]	70*[95]	r_{rup}	C	I50	1M	A (N, R, S, HW, AS)
Cotton *et al.* (2008)	Japan	3894	-	337	4	7.3	M_w (M_{JMA})	1	100	r_{rup} (r_{hypo} for small)	4[96] & 2[97]	G	2M	A
Humbert & Viallet (2008)	Europe & Middle East	960	-	138	4.0	7.4	M_s	U	U	r_{hypo}	1	U	O	A
Idriss (2008)	Worldwide shallow crustal	942	-	72	4.5	7.7	M_w	0.3	199.3	r_{rup}	2	I50	1	A (R/RO/NO, S/N)
Lin & Lee (2008)	NE Taiwan+10 foreign	4244+139	-	44+10	4.1 (6.0)	7.3 (8.1)	M_w (M_L)	15	630	r_{hypo}	2	G	1W	A (B, F)
Massa *et al.* (2008)	Northern Italy	306	306	82	3.5 & 4.0	6.3 & 6.5	M_w (M_L) & M_L	1*	100*	r_{epi}	3	L	1M	A
Mezcua *et al.* (2008)	Spain	250	-	149	3.1	5.3	M_w ($m_b(L_g)$)	5*	100*	r_{hypo}	1	U	1	A
Morasca *et al.* (2008)	Molise	3090	3090	100	2.7	5.7	M_L	12*	60*	r_{hypo}	2	L	1M	A
Slejko *et al.* (2008)	Caucasus (36–$46°$N, 38–$52°$E)	200	-	≥21	4.0*	8.1*	M_s (M_L, M_w, m_b)	2*	100*	r_{epi}	1	U	O	A
Srinivasan *et al.* (2008)	Kolar Gold Fields, India	795	-	795	0.5	3.0	M_L	1	4.76	r_{hypo}	1	G	1	A
Aghabarati & Tehranizadeh (2009)	Worldwide shallow crustal	678	678	55	5.2	7.9	M_w	0	60	r_{rup}	C	G	1M	A (N, R, S)
Akyol & Karagöz (2009)	Western Anatolia	168	-	49	4.03	6.40	M_w (M_d, M_L)	15	200	r_{hypo}	2	L	2M	A
Bindi *et al.* (2009a)	Italy	241	241	27	4.8	6.9	M_w	0	190	r_{jb} (r_{epi} for small)	3	L, G	1M	A (N, S, R)
Bindi *et al.* (2009b)	Italy	235	-	27	4.6	6.9	M_w (M_L)	0	183	r_{jb}, r_{epi}	3	L	1M	A

continued on next page

[92]Believe that model can be extrapolated down to 4.0.
[93]Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.
[94]Believe that model valid to $0\,\mathrm{km}$.
[95]Believe that model valid to $200\,\mathrm{km}$.
[96]For stations on surface.
[97]For borehole stations.

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Bragato (2009)	Italy	922	-	116	2.7	4.5	M_L	6	100	r_{epi}	I, 3, 1, C	U	1	A
Hong *et al.* (2009b)	Mexico (interface & inslab)	418, 277	-, -	40, 16	5.0, 5.2	8.0, 7.4	M_w	U	U	r_{rup} (r_{hypo} for small)	1	G, R, Q	1M	F, S
Hong *et al.* (2009a)	California	592	-	39	5*	7.3*	M_w	0.2*	100*	r_{jb}	C	G, R	1M, 2M, O	A
Kuehn *et al.* (2009)	Worldwide	2660	-	60	5.61	7.9*	M_w	0.1*	200*	r_{jb}	C	G	1M (O)	A (N, R, S)
Mandal *et al.* (2009)	Gujarat, India	248	-	33	3.1	7.7	M_w	1*	300*	r_{jb}	2	L	2	A
Moss (2009)	Worldwide shallow crustal	1950	-	125	4.265	7.90	M_w	0.2*	70*	r_{rup}	C	I50	1M	A (N, R, S, HW, AS)
Pétursson & Vogfjörd (2009)	SW Iceland	823	823	46	3.3	6.5	M_{Lw}	3	380	r_{epi}	1	V3	1	A
Rupakhety & Sigbjörnsson (2009)	South Iceland+others	64+29	-	12	5.02	7.67	M_w	1	97	r_{jb} (r_{epi} for some)	2	L	1	S & O
Akkar & Bommer (2010)	Europe & Middle East	532	-	131	5.0	7.6	M_w	0	99	r_{jb}	3	G	1M	A (N, S, R)
Akkar & Çağnan (2010)	Turkey	433	-	137	5.0	7.6	M_w	0*	200*	r_{jb}	C	G	1M	A (N, S, R)
Arroyo *et al.* (2010)	Pacific coast of Mexico	418	-	40	5.0	8.0	M_w	20	400	r_{rup} (r_{hypo} for $M_w < 6$)	1	U	O	F
Bindi *et al.* (2010)	Italy	561	561	107	4.0	6.9	M_w	1*	100*	r_{jb}, r_{epi}	3	L	1M	A
Cua & Heaton (2010)	Southern California+other shallow crustal	3588+1607	-	70	2 (5)	7.3 (7.9)	M_w	0.8 (0.1)*	200 (200)*	r_{jb} (r_{epi} for $M < 5$)	2	G	1	A
Douglas & Halldórsson (2010)	Europe & Middle East	595	-	135	5.0	7.6	M_w	0	99	r_{jb} (r_{epi} for small events)	3	L	1WM	A (N, T, S, O, AS)

continued on next page

Illustration 1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	C	R	M
Faccioli *et al.* (2010)	Worldwide shallow crustal	1499	-	≤ 60	4.5	7.6	M_w	0.2*	200*	r_{rup} (r_{hypo} for small)	4 & C	G	1M	A (N, R, S)
Graizer *et al.* (2010)	Worldwide	13992	-	245	4.2	7.9	M_w	0.1*	500*	r_{rup}	C	U	O	A (SN, R)
Hong & Goda (2010)	California[98]	592	-	39	5.0	7.28	M_w	0.2*	100*	r_{jb}	C	1, 2	1M	A
Jayaram & Baker (2010)	Worldwide shallow crustal	1561	-	64	4.27	7.90	M_w	0.07	199.27	r_{rup}	C	I50	O	A (N, R, S, HW)
Montalva (2010)	Japan	3894	-	337	4	7.3	M_w (M_{JMA})	1	100	r_{rup} (r_{hypo} for small)	C, I	G	O (1M)	A
Ornthammarath *et al.* (2010), Ornthammarath (2010) & Ornthammarath *et al.* (2011)	South Iceland	81	-	6	5.1	6.5	M_w	1*	80*	r_{jb} (r_{epi} for $M_w < 6$)	2	G	1M	S
Ulutas & Ozer (2010)	Marmara region, Turkey	751	-	78	4.0	7.4	M_w (M_d)	0.1	196.8	r_{jb}[99] (r_{epi} for small events)	1	L	1	SN

[98] Also derive models for inslab (273 records from 16 earthquakes) and interface (413 records from 40 earthquakes) Mexican earthquakes.
[99] Not entirely clear in the article if r_{rup} was actually used.

Chapter 4

Summary of published GMPEs for spectral ordinates

4.1 Johnson (1973)

- Ground-motion model is:

$$\text{PSRV} = C10^{\alpha m_b} R^m$$

- Response parameter is pseudo-velocity for 5% damping.
- Most (76%) records from $R < 70\,\text{km}$.
- Uses only shallow focus earthquakes of 'normal' or less depth, to minimize variables, except for one record from deeper earthquake ($m_b = 6.5$, $R = 61.1\,\text{km}$) which produces no distortion in statistical calculations.

4.2 McGuire (1974) & McGuire (1977)

- See Section 2.10.
- Response parameter is pseudo-velocity for 0, 2, 5 and 10% damping.
- Residuals pass Kolmogorov-Smirnov goodness-of-fit test at 5% significance level for normal distribution, so it is concluded that pseudo-velocities are lognormally distributed.
- Feels that using 16 natural periods presents a very good picture of spectral trends throughout entire period range.
- Only gives graphs of coefficients not actual calculated values.

4.3 Kobayashi & Nagahashi (1977)

- Ground-motion model is:

$$\log_{10} S_{V0} = a(\omega)M - b(\omega)\log_{10} x - c(\omega)$$

- Response parameter is velocity for unspecified[1] damping.

[1] It is probably 5%.

- Do regression iteratively. Assume $a(\omega)$, $b(\omega)$ and $c(\omega)$. Find amplification factors, $G_i(\omega)$, for each response spectra, $R_i(\omega)$: $G_i = R_i(\omega)/S_{V0}$. Calculate amplification factor, G, for each site: $G = \sqrt[n]{\prod_{i=1}^{n} G_i(\omega)}$. Estimate bedrock spectrum, $B_i(\omega)$, for each record: $B_i(\omega) = R_i(\omega)/G(\omega)$. Find $a(\omega)$, $b(\omega)$ and $c(\omega)$ by least squares. Repeat these steps until convergence. Hence find attenuation relation for bedrock and amplification function for each site.

4.4 Trifunac (1977) & Trifunac & Anderson (1977)

- Ground-motion model is:

$$\log_{10}[\mathrm{SA}(T), p] = M + \log_{10} A_0(R) - a(T)p - b(T)M - c(T) - d(T)s - e(T)v - f(T)M^2 - g(T)R$$

  where $\log A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of M_L, p is confidence level and v is component direction ($v = 0$ for horizontal and 1 for vertical). $\log A_0(R)$ not given here due to lack of space.

- Uses three site categories:

$s = 0$ Alluvium. 63% of data.

$s = 1$ Intermediate. 23% of data.

$s = 2$ Basement rock. 8% of data.

- Response parameter is acceleration for 0, 2, 5, 10 and 20% damping.

- Note that do not believe the chosen independent parameters are the best physical characterization of strong shaking but they are based on instrumental and qualitative information available to the engineering community in different parts of the USA and the world.

- Data from free-field stations and basements of tall buildings, which assume are not seriously affected by the surroundings of the recording station. Note that detailed investigations will show that data from basements of tall buildings or adjacent to some other large structure are affected by the structures but do not consider these effects.

- Equation constrained to interval $M_{\min} \le M \le M_{\max}$ where $M_{\min} = -b(T)/2f(T)$ and $M_{\max} = [1 - b(T)]/2f(T)$. For $M > M_{\max}$ replace $f(T)M^2$ by $f(T)(M - M_{\max})^2$ and for $M < M_{\min}$ replace M by $M_{\min}$ everywhere to right of $\log_{10} A_0(R)$.

- Use almost same data as Trifunac (1976). See Section 2.13.

- Use same regression method as Trifunac (1976). See Section 2.13.

- Note that need to examine extent to which computed spectra are affected by digitization and processing noise. Note that routine band-pass filtering with cut-offs of 0.07 and $25\,\mathrm{Hz}$ or between 0.125 and $25\,\mathrm{Hz}$ may not be adequate because digitisation noise does not have constant spectral amplitudes in respective frequency bands and because noise amplitudes depend on total length of record.

- Find approximate noise spectra based on 13 digitisations of a diagonal line processed using the same technique used to process the accelerograms used for the regression. Linearly interpolate noise spectra for durations of 15, 30, 60 and $100\,\mathrm{s}$ to obtain noise spectra for duration of record and then subtract noise spectrum from record spectrum. Note that since $\mathrm{SA}(y_1 + y_2) \neq \mathrm{SA}(y_1) + \mathrm{SA}(y_2)$ this subtraction is an approximate method to eliminate noise which, empirically, decreases the distortion by noise of the SA spectra when the signal-to-noise ratio is small.
- Note that p is not a probability but for values of p between 0.1 and 0.9 it approximates probability that $\mathrm{SA}(T)_{,p}$ will not be exceeded given other parameters of the regression.
- $-g(T)R$ term represents a correction to average attenuation which is represented by $\log_{10} A_0(R)$.
- Do not use data filtered at $0.125\,\mathrm{Hz}$ in regression for $T > 8\,\mathrm{s}$.
- Due to low signal-to-noise ratio for records from many intermediate and small earthquakes only did regression up to $12\,\mathrm{s}$ rather than $15\,\mathrm{s}$.
- Smooth coefficients using an Ormsby low-pass filter along the $\log_{10} T$ axis.
- Only give coefficients for 11 selected periods. Give graphs of coefficients for other periods.
- Note that due to the small size of $g(T)$ a good approximation would be $\log A_0(R) + R/1000$.
- Note that due to digitisation noise, and because subtraction of noise spectra did not eliminate all noise, $b(T)$, $c(T)$ and $f(T)$ still reflect considerable noise content for $T > 1 - -2\,\mathrm{s}$ for $M \approx 4.5$ and $T > 6 - -8\,\mathrm{s}$ for $M \approx 7.5$. Hence predicted spectra not accurate for periods greater than these.
- Note that could apply an optimum band-pass filter for each of the accelerograms used so that only selected frequency bands remain with a predetermined signal-to-noise ratio. Do not do this because many data points would have been eliminated from analysis which already has only a marginal number of representative accelerograms. Also note that such correction procedures would require separate extensive and costly analysis.
- Note that low signal-to-noise ratio is less of a problem at short periods.
- Compare predicted spectra with observed spectra and find relatively poor agreement. Note that cannot expect using only magnitude to characterise source will yield satisfactory estimates in all cases, especially for complex earthquake mechanisms. Additional parameters, such as a better distance metric than epicentral distance and inclusion of radiation pattern and direction and velocity of propagating dislocation, could reduce scatter. Note, however, that such parameters could be difficult to predict *a priori* and hence may be desirable to use equations no more detailed than those proposed so that empirical models do not imply smaller uncertainties than those associated with the input parameters.
- Plot fraction of data points, p_a which are smaller than spectral amplitude predicted for p values between 0.1 and 0.9. Find relationship between p_a and p. Note that response spectral amplitudes should be nearly Rayleigh distributed, hence $p_a(T) = \{1 - \exp[-\exp(\alpha(T)p + \beta(T)]\}^{N(T)}$. Find α, β and N by regression and smoothed

by eye. $N(T)$ should correspond to the number of peaks of the response of a single-degree-of-freedom system with period T but best-fit values are smaller than the value of $N(T)$ derived from independent considerations.

4.5 Faccioli (1978)

- See Section 2.18.
- Response parameter is pseudo-velocity for 5% damping.
- Plots all spectra. 2 records have abnormally high values in long period range, so remove and repeat. Results practically unaffected so leave them in.
- Notes that due to small size of sample, site and source correlation can introduce some error in coefficients because all data treated as statistically independent. Assume correlations are small so neglect error.

4.6 McGuire (1978)

- See Section 2.19.
- Response parameter is pseudo-velocity for 2% damping.

4.7 Trifunac (1978) & Trifunac & Anderson (1978a)

- Ground-motion model is (from definition of local magnitude scale):

$$\begin{aligned}\log[\mathrm{PSV}(T)_{,p}] &= M + \log A_0(R) - a(T)p - b(T)M - c(T) - d(T)s - e(T)v \\ &\quad - f(T)M^2 - g(T)R\end{aligned}$$

  where $\log A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of M_L, p is confidence level and v is component direction ($v = 0$ for horizontal and 1 for vertical). $\log A_0(R)$ not given here due to lack of space.

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Uses three site categories:

$s = 0$ Alluvium. 63% of data.

$s = 1$ Intermediate. 23% of data. Notes that ideally would not need but had to be introduced because in some cases difficult to make a choice in complex geological environment or because of insufficient data.

$s = 2$ Basement rock. 8% of data.

- Use same data as Trifunac & Anderson (1977). See Section 4.4.
- Use same regression method as Trifunac & Anderson (1977). See Section 4.4.

- Equation constrained to interval $M_{\min} \leq M \leq M_{\max}$ where $M_{\min} = -b(T)/2f(T)$ and $M_{\max} = [1 - b(T)]/2f(T)$. For $M > M_{\max}$ replace M by $M_{\max}$ everywhere and for $M < M_{\min}$ replace M by $M_{\min}$ in $b(T)M$ and $f(T)M^2$. This gives linear growth for $M < M_{\min}$, parabolic growth for $M_{\min} \leq M \leq M_{\max}$ and constant amplitude for $M > M_{\max}$.

- 98 records from San Fernando earthquake (9/2/1971) but regression method eliminated 70% of these before computing the coefficients.

- Epicentral distance used for simplicity, consistency with earlier studies and for lack of significantly better choice. Distance measure chosen has small effect whenever epicentral distance greater than several source dimensions.

- Notes that recording and processing noise in signal means that quality of coefficients diminishes for $T > 2\,\mathrm{s}$. Equations not recommended for periods longer than those for which selected spectral amplitudes plotted.

- Notes that equations should be considered only as preliminary and an empirical approximation to a complicated physical problem.

- Notes that data are limited to narrow magnitude interval, most data comes from alluvium sites and about half comes from one earthquake.

- Only gives coefficients for 11 periods. Graphs of coefficients for other periods.

4.8 Trifunac & Anderson (1978b)

- Ground-motion model is (from definition of local magnitude scale):

$$\begin{aligned}\log[\mathrm{PSV}(T)_{,p}] \quad = \quad & M + \log A_0(R) - a(T)p - b(T)M - c(T) - d(T)s - e(T)v \\ & - f(T)M^2 - g(T)R\end{aligned}$$

  where $\log A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of M_L, p is confidence level and v is component direction ($v = 0$ for horizontal and 1 for vertical). $\log A_0(R)$ not given here due to lack of space.

- Response parameter is velocity for 0, 2, 5, 10 and 20% damping.

- Uses three site categories:

$s = 0$ Alluvium. 63% of data.

$s = 1$ Intermediate. 23% of data. Notes that ideally would not need but had to be introduced because in some cases difficult to make a choice in complex geological environment or because of insufficient data.

$s = 2$ Basement rock. 8% of data.

- Use same data as Trifunac & Anderson (1977). See Section 4.4.

- Use same regression method as Trifunac & Anderson (1977). See Section 4.4.

- Equation constrained to interval $M_{\min} \leq M \leq M_{\max}$ where $M_{\min} = -b(T)/2f(T)$ and $M_{\max} = [1 - b(T)]/2f(T)$. For $M > M_{\max}$ replace M by $M_{\max}$ everywhere and for $M < M_{\min}$ replace M by $M_{\min}$ in $b(T)M$ and $f(T)M^2$. This gives linear growth for $M < M_{\min}$, parabolic growth for $M_{\min} \leq M \leq M_{\max}$ and constant amplitude for $M > M_{\max}$.
- Only gives coefficients for 11 periods. Graphs of coefficients for other periods.

4.9 Cornell *et al.* (1979)

- See Section 2.21.
- Response parameter is pseudo-velocity for 0, 2 and 10% damping.
- Consider different paths, e.g. going through intensities, Fourier spectra and PGA, to predict PSV. Note that direct paths have minimum variance but that going through intermediate steps does not significantly increase prediction uncertainty provided that intermediate parameters are representative of frequency band of structural system.
- Do not give coefficients.

4.10 Faccioli & Agalbato (1979)

- See Section 2.23.
- Response parameter is pseudo-velocity for 5% damping.

4.11 Trifunac & Lee (1979)

- Ground-motion model is:

  $$\log_{10} \mathrm{PSV}(T) = M + \log_{10} A_0(R) - b(T)M - c(T) - d(T)h - e(T)v - f(T)M^2 - g(T)R$$

  where $\log A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of M_L and v is component direction ($v = 0$ for horizontal 1 for vertical).
- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Use depth of sedimentary deposits, h, to characterise local geology.
- Depths of sedimentary and alluvial deposits at stations used are between 0 and about $6\,\mathrm{km}$ and most are less than about $4\,\mathrm{km}$.
- Use data and regression technique of Trifunac & Anderson (1977), see Section 4.4.
- Note no obvious physical reason why dependence of PSV on h should be linear. Try including terms with h^2, h^3 and higher powers of h but they lead to values which are undistinguishable from zero at 95% confidence level.
- Approximate significance tests show that coefficients are significantly different from zero in large subregions of the complete period range.

- Only give coefficients for 11 periods. Graphs of coefficients for other periods.
- Note results are only preliminary.
- Note amount of data too small to include more sophisticated independent parameters.

4.12 Ohsaki *et al.* (1980b)

- Ground-motion model is:

$$\log S_v = a'M - b'\log x - c'$$

- Response parameter is velocity for 5% damping.
- Use two soil conditions:

Group A Hard rock: geology consists of granite, andesite and shale of Miocene or earlier geological age, having S wave velocity $\gtrsim 1500\,\mathrm{m/s}$ or P wave velocity $\gtrsim 3000\,\mathrm{m/s}$, 60 records

Group B Rather soft rock: geology consists of mudstone of Pliocene or late Miocene age, having S wave velocity of about 500–$1000\,\mathrm{m/s}$, 35 records.

- Use records where geological and geotechnical conditions investigated in detail and considered to represent free-field rock motions. Exclude records suspected to be amplified by surface soil or affected by high topographical relief.
- Most records from $\geq 30\,\mathrm{km}$.
- Do regression on both site categories separately and give graphs of coefficients not tables.

4.13 Ohsaki *et al.* (1980a)

- See Section 2.28.
- Response parameter is velocity for 5% damping.
- Also give smoothed results using correction factors based on derived PGV equation.

4.14 Trifunac (1980)

- Ground-motion model is:

$$\log_{10}\mathrm{PSV}(T) = \begin{cases} M - \log_{10} A_0(R) - b(T)M_{\min} - c(T) - d(T)h - e(T)v \\ \quad - f(T)M_{\min}^2 - g(T)R \\ \quad \text{for} \quad M \leq M_{\min} \\ M - \log_{10} A_0(R) - b(T)M - c(T) - d(T)h - e(T)v \\ \quad - f(T)M^2 - g(T)R \\ \quad \text{for} \quad M_{\min} < M < M_{\max} \\ M_{\max} - \log_{10} A_0(R) - b(T)M_{\max} - c(T) - d(T)h - e(T)v \\ \quad - f(T)M_{\max}^2 - g(T)R \\ \quad \text{for} \quad M \geq M_{\max} \end{cases}$$

where $\log_{10} A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of M_L, v is component direction ($v = 0$ for horizontal and 1 for vertical), $M_{\min} = -b(T)/(2f(T))$ and $M_{\max} = (1 - b(T))/(2f(T))$.

- Response parameter is pseudo-velocity for $0, 2, 5, 10$ and 20% damping.
- Characterises site condition by depth of sedimentary and alluvial deposits beneath station, h. Uses records with $0 \leq h \leq 6\,\mathrm{km}$, with most $< 4\,\mathrm{km}$.
- Performs analysis to minimize possible bias due to uneven distribution of data among magnitude, site conditions and from abundance of data for some earthquakes.
- Tries terms with higher powers of h but coefficients are undistinguishable from zero at 95% confidence level.
- Assumes probability that $\log_{10} \mathrm{PSV}(T) - \log_{10} \mathrm{P\bar{S}V}(T) \leq \epsilon$, where $\log_{10} \mathrm{PSV}(T)$ is measured PSV and $\mathrm{P\bar{S}V}(T)$ is predicted PSV and ϵ is a probability, can be expressed as $p(\epsilon, T) = [1 - \exp(-\exp(\alpha(T)\epsilon(T) + \beta(T)))]^{N(T)}$. This assumption passes Kolmogorov-Smirnov and χ^2 tests at 95% level.
- Finds $a(T)$ through $g(T)$ significantly different than zero for large subregions of whole period range. $d(T)$ is only significantly different than zero for $T \gtrsim 0.3\,\mathrm{s}$.
- Gives coefficients of smoothed results for 11 periods.
- Notes only preliminary. Improvements should be based on physical nature of phenomenon using a functional form predicted by theory and experiment but due to lack of data cannot be done.

4.15 Devillers & Mohammadioun (1981)

- Ground-motion model is:

$$V(f) = C10^{\alpha M} R^n$$

- Response parameter is pseudo-velocity for $2, 5, 10$ and 20% damping.
- Most records from between 20 and $40\,\mathrm{km}$. No records from $R < 10\,\mathrm{km}$ so equation does not apply there.
- Eliminate suspect and/or redundant (San Fernando) records.
- Split data into intensity groups: VI (126 records), VII (56 records), V+VI (186 records), VI+VII (182 records) and VII+$\geq$ VIII (70 records) and calculates coefficients for each group.
- Note not adjusted for local site conditions. Try to distinguish effect but correlations do not reveal significant variations. Notes very few records on hard rock.
- Do not give coefficients only graphs of results.

4.16 Joyner & Boore (1982a)

- Ground-motion model is:

$$\begin{aligned}\log y &= \alpha + \beta M_p \log r + br + cS \\ r &= (d^2 + h^2)^{1/2}\end{aligned}$$

- Response parameter is pseudo-velocity for 5% damping.
- Use two site classes:

Rock $S = 1$

Soil $S = 0$

- Test magnitude dependence of h by selecting data from $< 10\,\mathrm{km}$ and plot residuals against M. Do not find any systematic relationship so conclude that data does not support a magnitude-dependent shape.
- Smooth coefficients using unspecified method.
- No data from rock sites with $d < 8\,\mathrm{km}$ and $M > 6$ so suggest caution in applying equations for rock sites at shorter distances and larger magnitudes. Also suggest caution in applying equations for $d < 25\,\mathrm{km}$ and $M > 6.6$ for either soil or rock because no data in this range. Also do not recommend equations for $M > 7.7$.

4.17 Joyner & Boore (1982b)

- See Section 2.33.
- Response parameter is pseudo-velocity for 5% damping.
- Use same data and method as Joyner & Boore (1982a).
- Restrict regressions to $T \leq 4\,\mathrm{s}$ to avoid problems due to record-processing errors.
- Find that coefficient for quadratic term is not statistically significant at 90% level for most periods but the values obtained at different periods are sufficiently consistent to warrant inclusion of this term. Note that maximum difference with and without quadratic term is about 20%.
- Include soil term at short periods even though not significant at 90% level.
- Smooth coefficients by plotting them against $\log T$ and drawing smooth curves.

4.18 Kobayashi & Midorikawa (1982)

- Ground-motion model is:

$$\begin{aligned}\log \mathrm{Sv}_0(T) &= a(T)(\log M_0 - c) - b(T)\log X + d \\ \text{where } a(T) &= a_1 + a_2 \log T \\ \text{and: } b(T)) &= \begin{cases} b_1(\log T)^2 + b_2 \log T + b_3 & \text{for: } 0.1 \leq T \leq 0.3\,\mathrm{s} \\ b_4 - b_5 \log T & \text{for: } 0.3 \leq T \leq 5\,\mathrm{s}\end{cases}\end{aligned}$$

- Response parameter is velocity for 5% damping.
- Magnitudes converted to seismic moment, M_0, by using empirical formula.
- Observed surface spectra divided by amplification over bedrock (assumed to have shear-wave velocity of $3\,\mathrm{km/s}$), calculated for each of the 9 sites.
- Note equation not for near field because earthquake is not a point source.

4.19 Joyner & Fumal (1984), Joyner & Fumal (1985) & Joyner & Boore (1988)

- See Section 2.37.
- Use data from Joyner & Boore (1982b).
- Response parameter is pseudo-velocity for 5% damping.
- shear-wave velocity not significant, at 90%, for periods 0.1, 0.15 and $0.2\,\mathrm{s}$ but significant for longer periods.
- Regression using shear-wave velocity and depth to rock shows significant correlation (decreasing ground motion with increasing depth) for long periods but small coefficients. Short periods do not show significant correlation.
- State inappropriate to use depth to rock for present data due to limited correlation and because San Fernando data is analysed on its own does not show significant correlation.

4.20 Kawashima *et al.* (1984)

- See Section 2.38.
- Response parameter is acceleration for 5% damping.

4.21 Kawashima *et al.* (1985)

- See section 2.43.
- Response parameter is acceleration for 5% damping.
- Variation of a and b with respect to T is due to insufficient number of records.

4.22 Trifunac & Lee (1985)

- Ground-motion models are (if define site in terms of local geological site classification):

  $$\log \mathrm{PSV}(T) = M + \mathrm{Att}(\Delta, M, T) + b_1(T)M + b_2(T)s + b_3(T)v + b_5(T) + b_6(T)M^2$$

  or (if define site in terms of depth of sediment):

  $$\log \mathrm{PSV}(T) = M + \mathrm{Att}(\Delta, M, T) + b_1(T)M + b_2(T)h + b_3(T)v + b_5(T) + b_6(T)M^2$$

where

$$\begin{aligned}
\mathrm{Att}(\Delta, M, T) &= \begin{cases} A_0(T)\log_{10}\Delta & \text{for} \quad R \leq R_{\max} \\ A_0(T)\log_{10}\Delta_{\max} - (R - R_{\max})/200 & \text{for} \quad R > R_{\max} \end{cases} \\
\Delta &= S\left(\ln\frac{R^2+H^2+S^2}{R^2+H^2+S_0^2}\right)^{-1/2} \\
\Delta_{\max} &= \Delta(R_{\max}, H, S) \\
R_{\max} &= \frac{1}{2}(-\beta+\sqrt{\beta^2-4H^2})
\end{aligned}$$

$S_0 = S_0(T)$ represents the coherence radius of the source and can be approximated by $S_0 \sim C_sT/2$, C_s is shear-wave velocity in source region (taken to be $1\,\mathrm{km/s}$), T is period, S is 'source dimension' approximated by $S = 0.2$ for $M < 3$ and $S = -25.34 + 8.151M$ for $3 \leq M \leq 7.25$ and v is component direction ($v = 0$ for horizontal 1 for vertical).

- Use two types of site parameter:
  - Local geological site classification:

    $s = 0$ Sites on sediments.

    $s = 1$ Intermediate sites.

    $s = 2$ Sites on basement rock.
  - Depth of sediments from surface to geological basement rock beneath site, h.
- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Equations only apply in range $M_{\min} \leq M \leq M_{\max}$ where $M_{\min} = -b_1(T)/(2b_6(T))$ and $M_{\max} = -(1+b_1(T))/(2b_6(T))$. For $M < M_{\min}$ use M only in first term of equation and $M_{\min}$ elsewhere and for $M > M_{\max}$ using $M_{\max}$ everywhere.
- Screen data to minimize possible bias in the model, which could result from uneven distribution of data among the different magnitude ranges and site conditions, or from excessive contribution to the database from several abundantly recorded earthquakes.
- Originally include a term linear in Δ, i.e. $b_4(T)\Delta/100$, but find that $b_4(T)$ is insignificant for most periods so deleted it.
- Use method of Trifunac & Anderson (1977) for residuals, see Section 4.4.

4.23 Kamiyama & Yanagisawa (1986)

- Ground-motion model is:

  $$\log_{10} V(T) = a(T)M_J - b(T)\log_{10}(\Delta+30) - d(T)D - c(T) + A_1(T)S_1 + \ldots + A_{N-1}(T)S_{N-1}$$

  where $S_i = 1$ for ith site and 0 otherwise.
- Response parameters are acceleration, velocity and displacement for 0, 2, 5 and 10% damping
- Model site amplification of each of the 26 sites individually by using S_i. Choose one site as bed rock site, which has S-wave velocity of about $1000\,\mathrm{m/s}$.

- Use records with PGA$> 20\mathrm{gal}$ ($0.2\,\mathrm{m/s^2}$).
- Focal depths, D, between 0 and $130\,\mathrm{km}$, with most between 10 and $50\,\mathrm{km}$.
- Find no significant differences between site amplification spectra for different response parameters or different damping levels.
- Compare amplification spectra from regression for different sites with those predicted using S-wave theory and find good agreement.
- Coefficients only given for velocity for 5% damping.

4.24 C.B. Crouse (1987) reported in Joyner & Boore (1988)

- See Section 2.48.
- Response parameter is pseudo-velocity for 5% damping.

4.25 Lee (1987) & Lee (1993)

- Ground-motion model is:

$$\begin{aligned}
\log_{10}[\widehat{\mathrm{PSV}}(T)] &= M_< + \mathrm{Att}(\Delta, M, T) + \hat{b}_1(T)M_{<>} + \hat{b}_2(T)h + \hat{b}_3(T)v \\
&\quad + \hat{b}_4(T)hv + \hat{b}_5(T) + \hat{b}_6(T)M_{<>}^2 + \hat{b}_7^{(1)}(T)S_L^{(1)} + \hat{b}_7^{(2)}(T)S_L^{(2)} \\
\text{where } M_< &= \min(M, M_{\max}) \\
M_{<>} &= \max(M_{\min}, M_<) \\
M_{\min} &= -\hat{b}_1/(2\hat{b}_6(T)) \\
M_{\max} &= -(1+\hat{b}_1(T))/(2\hat{b}_6(T))
\end{aligned}$$

where $v = 0$ for horizontal component, 1 for vertical, h is depth of sedimentary deposits beneath recording station and $\mathrm{Att}(\Delta, M, T)$ is same as Trifunac & Lee (1989) (see Section 4.33).

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Uses three site categories:

$S_L = 0$ Rock: 1 sediment site ($h > 0$), 11 intermediate sites ($h \sim 0$) and 13 bedrock sites ($h = 0$) $\Rightarrow S_L^{(1)} = 0$ & $S_L^{(2)} = 0$.

$S_L = 1$ Stiff soil ($\leq 45 - 60\,\mathrm{m}$ deep): 37 sediment sites ($h > 0$), 24 intermediate sites ($h \sim 0$) and 3 bedrock sites ($h = 0$) $\Rightarrow S_L^{(1)} = 1$ & $S_L^{(2)} = 0$.

$S_L = 2$ Deep soil: 44 sediment sites ($h > 0$) and 2 intermediate sites ($h \sim 0$) $\Rightarrow S_L^{(1)} = 0$ & $S_L^{(2)} = 1$.

- For $M > 6.5$ uses different (unspecified) magnitude scales because for seismic risk analysis often catalogues do not specify scale and often estimates are not homogeneous.
- Free-field records with both soil and alluvial depth information.

- Screens data to minimize possible bias due to uneven distribution of soil classification or excessive contribution from several abundantly recorded earthquakes.
- Gives smoothed coefficients for 12 periods.
- Uses method of Trifunac (1980) for uncertainties.
- Also uses method where site coefficients, $\hat{b}_7^{(1)}$ & $\hat{b}_7^{(2)}$, are found from residues from equation without site coefficients; find similar results.

4.26 K. Sadigh (1987) reported in Joyner & Boore (1988)

- See Section 2.51.
- Response parameter is pseudo-acceleration for 5% damping.

4.27 Annaka & Nozawa (1988)

- See Section 2.54.
- Response parameter is acceleration for 5% damping.
- Give only graphs of coefficients.

4.28 Crouse *et al.* (1988)

- Ground-motion model is:

$$\ln[\mathrm{PSV}(T)] = a + bM + c\ln[R] + dh$$

- Most data from shallow stiff soil and sedimentary deposits between about 5 and $25\,\mathrm{m}$ deep on Tertiary or older bedrock.
- Response parameter is pseudo-velocity for 5% damping.
- All earthquakes from Benioff-Wadati zones.
- Exclude data with magnitudes or distances well outside range of most selected records.
- Focal depths, h between 14 and $130\,\mathrm{km}$.
- No strong correlations between h, R and M.
- Try terms eM^2 and fR but find not significant (using t-test).
- Try term $R + C_1\exp(C_2M)$ instead of R; find similar standard errors.
- Find d is insignificant for 0.6 to $2\,\mathrm{s}$; find d does not significantly reduce standard errors.
- Find residuals are normally distributed (by plotting on normal probability paper and by Kolmogorov-Smirnov test).

- Split data by fault mechanism (thrust: 49 records, normal: 11 records, strike-slip: 4 records) and find attenuation equation for each subset; results are not significantly different (at 95% using F test). Also check by examining normal deviates (normalised residuals) for each subset and period; find no significant differences.
- Use 131 records from six other subduction zones (Nankai, Kuril, Alaska, Peru/N. Chile, Mexico and New Britain/Bougainville) to examine whether ground motions from all subduction zones are similar.
- Examine normal deviates for residuals between other zones' ground motion and N. Honshu equation. Find no significant differences (although obtain significant results for some periods and focal mechanisms) between N. Honshu, Kuril and Nankai motions. Find differences for Alaskan and Mexican data but could be due to site effects (because some data from soft soil sites). Find differences for Peru/N. Chile and New Britain/Bougainville which are probably source effects.
- Plot seismotectonic data (age, convergence rate, dip, contact width, maximum subduction depth, maximum historical earthquake (M_w), maximum rupture length, stress drop and seismic slip) against decreasing ground motion at stiff sites for $T > 0.8\,\mathrm{s}$. Find weak correlations for stress drop and M_w (if ignore Mexican data) but due to variability in stress drop estimates note lack of confidence in results.

4.29 Petrovski & Marcellini (1988)

- See Section 2.59.
- Response parameter is relative pseudo-velocity for 0.5%, 2%, 5% and 10% damping.

4.30 Yokota *et al.* (1988)

- Ground-motion model is:

$$\log S_v(T) = a(T)M + b(T)\log X + c(T)$$

- Response parameter is velocity for 5% damping.
- Focal depths between about 20 and $100\,\mathrm{km}$.
- Records from two stations in lowlands of Tokyo $3.7\,\mathrm{km}$ apart.
- Also analyse another region, using 26 records from 17 earthquakes with distances between 95 and $216\,\mathrm{km}$. Note difference in results between regions.
- Analyses vertical spectra from three small regions separately, one with 24 records with $4.0 \leq M \leq 6.1$ and $60 \leq X \leq 100\,\mathrm{km}$, one with 22 records with $4.2 \leq M \leq 6.0$ and $68 \leq X \leq 99\,\mathrm{km}$ and one with 5 records with $4.4 \leq M \leq 6.0$ and $59 \leq X \leq 82\,\mathrm{km}$.
- Give no coefficients, only results.

4.31 Youngs *et al.* (1988)

- See Section 2.62.
- Ground-motion model is:

$$\ln(S_v/a_{\max}) = C_6 + C_7(C_8 - M_w)^{C_9}$$

- Response parameter, S_v, is velocity[2] for 5% damping
- Develop relationships for ratio $S_v/a_{\max}$ because there is a much more data for PGA than spectral ordinates and use of ratio results in relationships that are consistent over full range of magnitudes and distances.
- Calculate median spectral shapes from all records with $7.8 \leq M_w \leq 8.1$ (choose this because abundant data) and $R < 150\,\mathrm{km}$ and one for $R > 150\,\mathrm{km}$. Find significant difference in spectral shape for two distance ranges. Since interest is in near-field ground motion use smoothed $R < 150\,\mathrm{km}$ spectral shape. Plot ratios $[S_v/a_{\max}(M_w)]/[S_v/a_{\max}(M_w = 8)]$ against magnitude. Fit equation given above, fixing $C_8 = 10$ (for complete saturation at $M_w = 10$) and $C_9 = 3$ (average value obtained for periods $> 1\,\mathrm{s}$). Fit C_7 by a linear function of $\ln T$ and then fix C_6 to yield calculated spectral amplifications for $M_w = 8$.
- Calculate standard deviation using residuals of all response spectra and conclude standard deviation is governed by equation derived for PGA.

4.32 Kamiyama (1989)

- Ground-motion model is:

$$\log_{10} V(\omega) = \log_{10} M_0 - a(\omega)\log_{10} r + b(\omega)\log_{10} L + e(\omega)r + c(\omega) + \sum_{j=1}^{N-1} A_j(\omega)S_j$$

  where $S_j = 1$ for site j and $S_j = 0$ otherwise.
- Response parameter is velocity for 0% damping.
- Uses same data as Kamiyama & Yanagisawa (1986).
- Uses same regression method as Kamiyama & Yanagisawa (1986).
- Focal depths between 0 and $130\,\mathrm{km}$.
- Uses fault length, L, for 52 records. For others where such data does not exist uses $M_0 = 10^{(1.5\log_{10} S + 22.3)}$, $S = 10^{M-4.07}$ and $L = \sqrt{S/2}$ where S is fault area in km^2.
- Chooses hard slate site with shear-wave velocity of 1–$2\,\mathrm{km/s}$ as ‘basic site’.
- Does not give coefficients, only graphs of coefficients.

[2] In paper conversion is made between S_v and spectral acceleration, S_a, suggesting that it is pseudo-velocity.

4.33 Trifunac & Lee (1989)

- Ground-motion model is:

$$\begin{aligned}\log_{10}[\mathrm{PSV}(T)] &= M + \mathrm{Att}(\Delta, M, T) + b_1(T)M + b_2(T)h + b_3(T)v + b_5(T) \\ &\quad + b_6(T)M^2 \\ \text{where } \mathrm{Att}(\Delta, M, T) &= A_0(T)\log_{10}\Delta \\ A_0(T) &= \begin{cases} -0.732025 \quad \text{for:} \quad T > 1.8\,\mathrm{s} \\ -0.767093 + 0.271556\log_{10}T - 0.525641(\log_{10}T)^2 \\ \qquad\qquad\qquad\qquad\qquad\qquad \text{for:} \quad T < 1.8\,\mathrm{s} \end{cases} \\ \Delta &= S\left(\ln\frac{R^2 + H^2 + S^2}{R^2 + H^2 + S_0^2}\right)^{-1/2} \\ S &= 0.2 + 8.51(M - 5)\end{aligned}$$

  where $v = 0$ for horizontal component and 1 for vertical, Δ is representative distance, S_0 is correlation radius of source function (or coherence size of source) (which can be approximated by $C_sT/2$, where C_s is shear wave velocity), h is depth of sedimentary deposits beneath recording station and H is focal depth.

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.

- Screen data to minimize possible bias due to uneven distribution of data among different magnitude ranges and site conditions or from excessive contribution to database from several abundantly recorded earthquakes.

- Include term, $b_4(T)\Delta/100$, but insignificant for most periods so remove.

- Equation only applies for $M_{\min} \leq M \leq M_{\max}$, where $M_{\min} = -b_1(T)/(2b_6(T))$ and $M_{\max} = -(1 + b_1(T))/(2b_6(T))$. For $M \leq M_{\min}$ use $M_{\min}$ everywhere except first term. For $M \geq M_{\max}$ use $M_{\max}$ everywhere.

- Use method of Trifunac (1980) for uncertainties.

- Note estimates should only be used where signal to noise ratio (based on estimated digitisation noise) not much less than unity or slope in log-log scale is not significantly greater than -1.

- Also fit data to $\log_{10}\mathrm{PSV}(T) = M + \mathrm{Att}(\Delta, M, T) + b_1(T)M + b_2(T)s + b_3(T)v + b_5(T) + b_6(T)M^2$ (where $s = 0$ for sediment sites, 1 for intermediate sites and 2 for basement rock sites) because depth of sediment not always known.

4.34 Atkinson (1990)

- Ground-motion model is:

$$\log y = c_1 + c_2(\mathbf{M} - 6) + c_3(\mathbf{M} - 6)^2 - \log R - c_4R$$

- Response parameter is pseudo-velocity for 5% damping.

- All data from rock sites.

- Includes only if a reliable seismic moment estimate exists.

- Converts ECTN vertical seismograms to equivalent horizontal component by multiplying by 1.4.
- Includes Nahanni (western Canada) earthquakes because exhibit dominant characteristics of eastern North American shocks (low seismicity area, high horizontal compressive stress, thrust mechanisms dominant, no surface ruptures despite shallow focus and rocks have high seismic velocity).
- Excludes US digital strong-motion Saguenay records due to low resolution. Two effects on response spectra: i) high frequencies contaminated by a 'mathematical noise' floor, ii) significant errors in amplitudes of low to intermediate frequencies (severity dependent on resolution degree). Inclusion of such data could lead to significant misinterpretation of these earthquakes.
- Most records (66, 65%) from $R \geq 111\,\mathrm{km}$ and $\mathbf{M} \leq 5.22$.
- Examines residuals from equations. Finds no persistent trends except for Saguenay data ($\mathbf{M} = 6$) between $63 \leq R \leq 158\,\mathrm{km}$.
- Notes data very limited in large magnitude range and that one or two earthquakes are controlling predictions.
- Notes different regression technique could change predictions for large magnitudes but i) data too limited to warrant more sophisticated analysis and ii) may be other factors, in addition to number of recordings, which should be considered in weighting each earthquake.

4.35 Campbell (1990)

- See Section 2.68.
- Response parameter is pseudo-velocity for 5% damping.

4.36 Dahle *et al.* (1990b) & Dahle *et al.* (1990a)

- See Section 2.69.
- Response parameter is pseudo-velocity for 5% damping.
- Coefficients only given for 7 periods; graphs for others.

4.37 Tamura *et al.* (1990)

- Ground-motion model is:

$$S_A(T_i, \mathrm{GC}) = a(T_i, \mathrm{GC})10^{b(T_i,\mathrm{GC})M}(\Delta + 30)^{C(T_i,\mathrm{GC})}$$

- Response parameter is acceleration for 2 and 5% damping.
- Use three site categories (GC) for which perform separate regression:

Group 1 Ground characteristic index $\lesssim 0.67$, 29 records.

Group 2 Ground characteristic index between about 0.67 and 1.50, 46 records.

Group 3 Ground characteristic index $\gtrsim 1.50$, 22 records.

where the ground characteristic index is calculated from statistical analysis of amplitude of records. Thought to reflect the characteristic of deep soil deposits at site (1.0 means amplification is average for Japan, < 1.0 or > 1.0 means amplification is lower or greater, respectively, than average for Japan).

- Records from JMA low-magnification mechanical seismographs (natural period $6\,\mathrm{s}$, damping ratio 0.55) which were instrument corrected (because sensitivity for periods $> 10\,\mathrm{s}$ is substantially suppressed) , filtered (cut-offs 1.3–$2\,\mathrm{s}$ and 20–$30\,\mathrm{s}$ chosen from a study of recording accuracy of instruments) and differentiated in frequency domain to find ground velocity and acceleration. Hence limit analysis to 2 to $20\,\mathrm{s}$.
- Do not use resultant of two horizontal components because two components not synchronous.
- Find difference in predicted ground motion using derived equations and those from earlier equations for short periods. Find that b for earlier equations increases almost linearly with logarithm of natural period, T, so find equation, by least squares, connecting b and $\log T$. Assume this equation holds for 2 to $20\,\mathrm{s}$ and so fix b and recalculate a and c; find predictions now agree.
- Only give graphs for original coefficients for 5% damping. Give tables of coefficients for preferred second analysis.

4.38 Tsai *et al.* (1990)

- See Section 2.73.
- Response parameter is acceleration for 5% damping.
- Also give equations for average acceleration for 2 period bands 0.12–$0.33\,\mathrm{s}$ and 0.07–$0.2\,\mathrm{s}$.

4.39 Crouse (1991)

- See Section 2.75.
- Response parameter is pseudo-velocity for 5% damping.
- Focal depths, h, between 10 and $238\,\mathrm{km}$.
- Notes that spectral database is biased to higher ground motions (because only higher ground motions are digitised). Suggest either using a different form of equation or impose constraints. Do not do either because (1) consider sample adequate for regression and (2) although overestimate smaller, more distant motion, it would properly estimate larger motions which are of greater concern for design applications.
- Sets p_3, p_5 and p_6 to those for PGA equation after trial regressions; does not appreciably affect standard deviation.

- Finds relatively larger standard deviation for 3.0 and $4.0\,\mathrm{s}$ which suggests form of equation may be inappropriate for longer periods.
- Plots normalised residuals (not shown) which show uniform distribution.

4.40 Dahle *et al.* (1991)

- Ground-motion model is:

$$\begin{aligned}\ln A &= c_1 + c_2 M + c_4 R + \ln G(R, R_0)\\ \text{where } G(R, R_0) &= R^{-1} \quad \text{for} \quad R \le R_0\\ \text{and: } G(R, R_0) &= R_0^{-1}\left(\frac{R_0}{R}\right)^{5/6} \quad \text{for} \quad R > R_0\end{aligned}$$

  this equation assumes spherical spreading (S waves) to R_0 and cylindrical spreading with dispersion (Lg waves) for larger distances.
- Response parameter is pseudo-velocity for 5% damping.
- All data from solid rock sites.
- Follow-on study to Dahle *et al.* (1990b) and Dahle *et al.* (1990a) but remove Chinese and Friuli data and data from border zone of Eurasian plate, so data is a more genuine intraplate set.
- Use 395 records from Norwegian digital seismograms. Require that the Lg displacement amplitude spectra should have a signal-to-noise ratio of a least 4 in the frequency range 1–$10\,\mathrm{Hz}$, when compared to the noise window preceding the P-wave arrival.
- For the selected seismograms the following procedure was followed. Select an Lg window, starting at a manually picked arrival time and with a length that corresponds to a group velocity window between 2.6 and $3.6\,\mathrm{km/s}$. Apply a cosine tapering bringing the signal level down to zero over a length corresponding to 5% of the data window. Compute a Fast Fourier Transform (FFT). Correct for instrument response to obtain true ground motion displacement spectra. Bandpass filter the spectra to avoid unreasonable amplification of spectral estimates outside the main response of the instruments. Passband was between $0.8\,\mathrm{Hz}$ and 15 or $20\,\mathrm{Hz}$, dependent on sampling rate. The amplitude spectra obtained using the direct method, using $A = \Delta t\sqrt{ZZ^*}$ where Δt is time step and Z is Fourier transformed time-history and Z^* is its complex conjugate. Convert instrument corrected displacement Lg Fourier transforms to acceleration by double differentiation and an inverse FFT.
- Use 31 accelerograms from eastern N. America, N. Europe and Australia.
- Use $R_0 = 100\,\mathrm{km}$ although note that R_0 may be about $200\,\mathrm{km}$ in Norway.
- Correlation in magnitude-distance space is 0.20.
- Use a variant of the two-stage method to avoid an over-representation of the magnitude scaling terms at small magnitudes. Compute average magnitude scaling coefficients within cells of 0.2 magnitude units before the second stage.

- Resample data to make sure all the original data is used in a variant of the one-stage method. Compute new (resampled) data points as the average of one or more original points within a grid of cells $160\,\mathrm{km}$ by 0.4 magnitude units. Correlation in resampled magnitude-distance space is 0.10.
- Find estimated ground motions from one-stage method systematically higher than those from two-stage method particularly at short distances and large magnitudes. Effect more significant for low frequencies. Find that this is because one-stage method gives more weight to supplementary accelerograph data from near field of large earthquakes.
- Standard deviations similar for one- and two-stage equations.
- Scatter in magnitude scaling coefficients from first stage of two-stage method is greater for strong-motion data.
- Try fixing the anelastic decay coefficient (c_4) using a previous study's results. Find almost identical results.
- Remove 1 record from Nahanni earthquake ($M_s = 6.9$) and recompute; only a small effect.
- Remove 17 records from Saguenay earthquake ($M_s = 5.8$) and recompute; find significant effect for large magnitudes but effect within range of variation between different regression methods.

4.41 Geomatrix Consultants (1991), Sadigh *et al.* (1993) & Sadigh *et al.* (1997)

- See Section 2.77
- Ground-motion model for deep soil is:

$$\ln y = C_1 + C_2 M - C_3 \ln(r_{\rm rup} + C_4 e^{C_5 M}) + C_6 + C_7(8.5 - M)^{2.5}$$

  where C_6 is different for reverse and strike-slip earthquakes.

  Ground-motion model for rock is:

$$\ln y = C_1 + C_2 M + C_3(8.5 - M)^{2.5} + C_4 \ln(r_{\rm rup} + \exp(C_5 + C_6 M)) + C_7 \ln(r_{\rm rup} + 2)$$

  where C_1 is different for reverse and strike-slip earthquakes.

  Vertical equations do not include C_7.
- Response parameter is acceleration for 5% damping.
- Perform analysis on spectral amplification $\ln(\mathrm{SA/PGA})$.
- Give smooth coefficients.
- Find standard errors to be dependent on magnitude and fit to a linear relation.

4.42 I.M. Idriss (1991) reported in Idriss (1993)

- See section 2.79.
- Response parameter is pseudo-acceleration for 5% damping.

4.43 Loh *et al.* (1991)

- See Section 2.80.
- Response parameters are acceleration, velocity and displacement for 5% damping.
- Only give coefficients for acceleration for periods $\geq 0.1\,\mathrm{s}$.

4.44 Matuschka & Davis (1991)

- See Section 2.81.
- Response parameter is acceleration for 5% damping.

4.45 Mohammadioun (1991)

- Ground-motion model is:

$$\log \mathrm{PSV}(f) = k(f) + a(f)M + n(f)R$$

- Response parameter is pseudo-velocity for 5%.
- Records not baseline corrected so no equations for periods $> 2\,\mathrm{s}$.
- Does not split up data into subsets by intensity because risk of creating data populations which are not statistically significant.
- Notes that could be inconsistency with using both r_{hypo} and r_{rup}.
- Notes that results are preliminary.
- Also analyses wide range of Californian data for 96 periods between 0.013 and $5\,\mathrm{s}$ split into two intensity dependent subsets: those records with site intensities VI-VII (326 records) and those with site intensities VII+ (156 records). Uses r_{rup} except for Imperial Valley earthquake where uses r_E. Does not use include soil or other variables because poorly defined and lead to selection of records that are not statistically valid.

4.46 Stamatovska & Petrovski (1991)

- See Section 2.84.
- Response parameter is pseudo-velocity for 0, 0.5, 1, 2, 5, 7, 10 and 20% damping.

4.47 Benito *et al.* (1992)

- Ground-motion model is:

$$\ln \frac{\mathrm{PSA}}{\mathrm{PSV}} = c_1 + c_2 M + c_3 \ln(R + R_0) + c_4(R + R_0)$$

- Response parameters are pseudo-acceleration, PSA, and pseudo-velocity, PSV, for 5% damping[3].
- Use three soil conditions (revised when cross hole information was available):

$S = 0$ Hard and rock sites, 50 records.

$S = 1$ Intermediate soil, 10 records.

$S = 2$ Soft soil, 12 records.

- Use M_L because most suitable for distance range of majority of records.
- Try including $c_5 S$ term but find low significance values for c_5. Repeat regression for each soil category separately. Give results when coefficient of determination $R^2 > 0.80$, standard errors $< 25\%$ and coefficients have high significance levels.
- For PSA for $S = 0$ give coefficients for all periods, for $S = 1$ give coefficients for 0.17 to $0.2\,\mathrm{s}$ and for $S = 2$ give coefficients for 1 to $10\,\mathrm{s}$.
- Also consider Friuli records ($4.2 \leq M_L \leq 6.5$, epicentral distances between 2 and $192\,\mathrm{km}$, 14 records for $S = 0$, 23 records for $S = 1$ and 16 records for $S = 2$).
- Note need to include term in model reflecting explicitly local amplification dependent on natural period of soil as well as predominant period of incident radiation to bed rock.

4.48 Niazi & Bozorgnia (1992)

- See Section 2.82.
- Response parameter is pseudo-velocity for 5% damping.
- For some periods ($0.20\,\mathrm{s}$ for vertical and 0.10 and $0.111\,\mathrm{s}$ for horizontal) constrain c_2 to zero so that predicted amplitude would not decrease with increasing magnitude at zero distance. Note that does not affect uncertainty.
- Note that long period filter cutoff may be too long for records from small shocks but if a shorter period was used then information on long period spectral ordinates would be lost. Note that insufficient data for well constrained results at $M = 5$ or $M > 7$.
- Find evidence for long period noise in d and in Degree of Magnitude Saturation ($\mathrm{DMS} = -(c_2 d/b) * 100$).
- Examine median and normalized standard deviation (coefficient of variation) and find evidence for decreasing uncertainty with increasing magnitude.

[3]Although coefficients should only differ by a constant because $\mathrm{PSA} = (2\pi/T)\mathrm{PSV}$ they do not; hence response parameters are probably not those stated.

4.49 Silva & Abrahamson (1992)

- See Section 2.89.
- Response parameter is pseudo-acceleration for 5% damping.
- Ground-motion model for PSA to PGA ratio is:

$$\ln(\text{Sa/pga}) = c_1 + c_3 r + c_4\{1 - \tanh[(r^{1.1} - 10)/3]\}(1 - F)$$

- Regress on ratio of PSA to PGA ratio because more stable than regression on absolute values.
- Choice of functional form guided by numerical simulations and previous empirical studies. Numerical simulations suggest that strike-slip events maybe more likely to show near-field directivity effects at long periods than dip-slip events.
- Data does not allow magnitude dependency to be reliably determined hence not modelled.
- Judge whether long period motion is realistic based on consistency of amplitudes and timing of long period energy and that of higher frequency motions. Expect that seismic ground motions have consistent phase structure at long periods whereas noise will have random phase. Examine the analytical derivative of the phase with respect to frequency and chose the upper period of reliable PSAs based on the period at which the phase derivative becomes more random.
- Only use PSAs for frequencies greater than 1.25 times the high-pass filter corner frequency and for periods less than the shortest period at which phase derivative is not well behaved. Note that these criteria tend to bias regression to larger spectral values because these will be above noise level more often than smaller motions. Do not try to correct for this bias.
- For $\geq 10\,\mathrm{s}$ insufficient data to yield stable coefficients. Based on numerical simulations, find response spectra are approximately flat for $> 8\,\mathrm{s}$ and $M < 7.5$ and, therefore, extend model to $20\,\mathrm{s}$ by assuming constant spectral displacement. Note that may not be appropriate for $M > 7.5$.
- Note that Loma Prieta is major contributor to dataset, which may explain strong distance dependency of spectral shape.

4.50 Tento *et al.* (1992)

- See Section 2.91.
- Response parameter is pseudo-velocity for 5% damping.
- Note that correction procedure significantly affects results for $T > 2\,\mathrm{s}$. Correction procedure introduces dishomogeneity and errors due to subjectivity of choice of low frequency filter limits.

4.51 Abrahamson & Silva (1993)

- See Section 2.93.
- Response parameter is pseudo-acceleration for 5% damping.
- Ground-motion model for PSA to PGA ratio is:

$$
\begin{aligned}
\text{For } M > 6.5&: \\
\ln(\text{Sa/pga})_{soil} &= c_1 + c_2(8.5 - M)^{c_8} + c_6 r + c_5\{1 - \tanh[(r - c_9)/c_{10}]\}(1 - F_1) \\
\text{For } M > 6.5&: \\
\ln(\text{Sa/pga})_{rock} &= c_3 + c_4(8.5 - M)^{c_8} + c_7 r + c_5\{1 - \tanh[(r - c_9)/c_{10}]\}(1 - F_1) \\
\text{For } 6 \leq M \leq 6.5&: \\
\ln(\text{Sa/pga})_{soil} &= c_1 + c_2(8.5 - M)^{c_8} + c_6 r \\
&\quad + 2(M - 6)c_5\{1 - \tanh[(r - c_9)/c_{10}]\}(1 - F_1) \\
\text{For } 6 \leq M \leq 6.5&: \\
\ln(\text{Sa/pga})_{rock} &= c_3 + c_4(8.5 - M)^{c_8} + c_7 r \\
&\quad + 2(M - 6)c_5\{1 - \tanh[(r - c_9)/c_{10}]\}(1 - F_1)
\end{aligned}
$$

- Regress on ratio of PSA to PGA ratio because more stable than regression on absolute values.
- Choice of functional form guided by numerical simulations and previous empirical studies. Numerical simulations suggest that strike-slip events maybe more likely to show near-field directivity effects at long periods than dip-slip events.
- Interested in long-period motions. Apply new accelerogram processing procedure to evaluate reliable long-period range based on Fourier phase spectra. Apply high-pass filter in frequency domain and a polynomial baseline correction in time domain. Judge whether long period motion is realistic based on consistency of amplitudes and timing of long period energy and that of higher frequency motions. Expect that seismic ground motions have consistent phase structure at long periods whereas noise will have random phase. Examine the analytical derivative of the phase with respect to frequency and chose the upper period of reliable PSAs based on the period at which the phase derivative becomes more random.
- Only use PSAs for frequencies greater than 1.25 times the high-pass filter corner frequency and for periods less than the shortest period at which phase derivative is not well behaved. Note that these criteria tend to bias regression to larger spectral values because these will be above noise level more often than smaller motions. Do not try to correct for this bias.
- For $\geq 10\,\mathrm{s}$ insufficient data to yield stable coefficients. Based on numerical simulations, find response spectra are approximately flat for $> 8\,\mathrm{s}$ and $M < 7.5$ and, therefore, extend model to $20\,\mathrm{s}$ by assuming constant spectral displacement. Note that may not be appropriate for $M > 7.5$.
- Compare predictions to spectrum of Landers 1992 ($M_w 7.5$) recorded at Lucerne station. Find that model overpredicts observation.

4.52 Boore *et al.* (1993) & Boore *et al.* (1997)

- See Section 2.94
- Response parameter is pseudo-velocity for 2, 5, 10 and 20% damping.
- Cutoff distance is lesser of distance to first digitized record triggered by S wave, distance to closest non-digitized recording, and closest distance to an operational nontriggered instrument.
- Note that can only use response spectral values between 0.1 and $2\,\mathrm{s}$ because of low sampling rate of older data (sometimes only 50 samples/sec) and low signal to noise ratios and filter cutoffs.
- Site categories same as in Section 2.94 but due to smaller dataset number of records in each category is less. Class A: 12 records, B: 51 records, C: 49 records.
- Smoothed coefficients using a least-squares fit of a cubic polynomial.

4.53 Caillot & Bard (1993)

- Ground-motion model is:

$$\ln y = \beta_1 + \beta_2 M + \beta_3 \ln \mathrm{HYPO} + \beta_4 S_1$$

- Response parameter is acceleration for 5% damping.
- Consider three site conditions but only retain two:
  1. Rock: ENEA/ENEL S0 classification $\Rightarrow S_1 = 0$, 49 records.
  2. Thin alluvium: depth of soil between 5 and $20\,\mathrm{m}$,ENEA/ENEL S1 classification $\Rightarrow S_1 = 1$, 34 records.
- Selected records have $d_e < 60\,\mathrm{km}$ and focal depth less than $30\,\mathrm{km}$. Data selected so that mean and standard deviation of magnitude and hypocentral distance in each site category are equal, in this case 5.1 and $20\,\mathrm{km}$ respectively.
- All records processed using common procedure. High pass filtered with $f_l = 0.5\,\mathrm{Hz}$, instrument corrected and low pass filtered with $f_h = 30\,\mathrm{Hz}$.
- Considered three things when choosing method of analysis:
  1. Attenuation equation must have some physical basis.
  2. Parameters must be available for original data set.
  3. Attenuation equation must be easy to use in a predictive manner.
- Hypocentral distance used because rupture not known for most earthquakes. Note that only important for magnitudes greater than about 6.5 and distances less than about $15\,\mathrm{km}$.
- Originally included another set of data (32 records) from thick soil with depth greater than about $20\,\mathrm{m}$ (ENEA/ENEL classification S2) but note that results for this category are much more uncertain, possibly due to diversity of geotechnical characteristics of soils. Therefore excluded.

- Regression was done using two-stage algorithm (Joyner & Boore, 1981) and a weighted one-stage method. Weight by splitting the magnitude and distance ranges into four intervals and weighting data in each interval inversely proportionally to number of points in the bin. Thus gives roughly equal weight to each part of magnitude-distance space.
- Note that results from two-stage regression for this set of data may be misleading because for some periods it does not bring any 'explanation' to the variance of initial data. The two-stage and normal one-stage and weighted one-stage yield significant changes in predictions.
- Repeat analysis using only S0 subset and using only S1 subset but no significant changes in magnitude or distance scaling between the two subsets so consider complete set and include a constant scaling between rock and shallow soil. If set is reduced to 53 records with similar spread of magnitude, distance and sites then difference between shallow soil and rock is not significant.
- Note that confidence interval should be given by formula in Weisburg (1985) not normal way of simply using standard deviation.

4.54 Campbell (1993)

- See Section 2.95.
- Response parameter is pseudo-acceleration for 5% damping.
- Notes that equation can predict smaller pseudo-acceleration than PGA for short periods, which is impossible in practice. Hence pseudo-acceleration for periods $\leq 0.2\,\mathrm{s}$ should be constrained to be $\geq$ PGA.

4.55 Electric Power Research Institute (1993a)

- Ground-motion model is:

$$\ln[y(f)] = C_1 + C_2(M-6) + C_3(M-6)^2 + C_4\ln(R) + C_5R + C_6Z_{SS} + C_7Z_{IS} + C_8Z_{DS}$$

- Response parameter is acceleration for 5% damping.
- Use three site classes

  SS Shallow soil (depth to rock $< 20\,\mathrm{m}$). $Z_{SS} = 1$, $Z_{IS} = 0$ and $Z_{DS} = 0$.

  IS Intermediate soil (depth to rock between 20 and $100\,\mathrm{m}$). Very limited data. $Z_{IS} = 1$, $Z_{SS} = 0$ and $Z_{DS} = 0$.

  DS Deep soil (depth to rock more than $100\,\mathrm{m}$). $Z_{DS} = 1$, $Z_{SS} = 0$ and $Z_{IS} = 0$.

  Cannot also examine effect of rock type (hard crystalline; hard sedimentary; softer, weathered; soft over hard) because of lack of data from non-crystalline sites in SS and IS classes.
- Collect all data from strong-motion instruments in eastern North America (ENA) and all seismographic network data from $m_b \geq 5.0$ at $\leq 500\,\mathrm{km}$. Also include some data from Eastern Canadian Telemetered Network (ECTN).

- Most data from $M < 5$ and $> 10\,\mathrm{km}$.
- Roughly half the data from aftershocks or secondary earthquakes in sequences.
- Limit analysis to $M \geq 4$ because focus is on ground motions of engineering interest.
- Use geometric mean to avoid having to account for correlation between two components.
- Note the large error bars on C_3, C_5 shows that data does not provide tight constraints on magnitude scaling and attenuation parameters.
- Do not provide actual coefficients only graphs of coefficients and their error bars.
- Find smaller inter-event standard deviations when using m_{Lg} than when using M_w.
- Examine effect on standard deviation of not including site terms. Compute the statistical significance of the reduction using the likelihood ratio test. Conclude that the hypothesis that the site terms are zero cannot be rejected at any period.
- Split data by region: the Gulf Coast (no records), the rest of ENA or a subregion of ENA that may have marginally different attenuation characteristics. Add dummy variable to account for site location in one of the two zones with data and another dummy variable for earthquake and site in different zones. Neither variable is statistically significant due to the limited and scattered data.
- Try fitting a bilinear geometric spreading term but find that the reduction in standard deviation is minimal.

4.56 Sun & Peng (1993)

- See section 2.101.
- Response parameter is acceleration for 5% damping.
- Coefficients not given.

4.57 Boore *et al.* (1994a), Boore *et al.* (1997) & Boore (2005)

- See Section 2.103
- Find no evidence for magnitude dependent uncertainty for spectral values.
- Find no evidence for amplitude dependent uncertainty for spectral values.
- Note that effect of basin-generated surface waves can have an important effect but probably not at periods between 0.1 and $2\,\mathrm{s}$.

4.58 Climent *et al.* (1994)

- Inspect observed and predicted values and conclude no clear difference between upper-crustal and subduction zone ground motions. Equations are for region regardless of earthquake source type.

4.59 Fukushima *et al.* (1994) & Fukushima *et al.* (1995)

- See Section 2.105.
- Response parameter is pseudo-velocity for 5% damping.
- Only give graphs of coefficients.
- Note possible noise contamination, for periods $< 0.1\,\mathrm{s}$, in coefficients.

4.60 Lawson & Krawinkler (1994)

- See Section 2.106.
- Response parameter is acceleration for 5% damping.

4.61 Lee & Manić (1994) & Lee (1995)

- Ground-motion model is:

$$
\begin{aligned}
\log_{10}\widehat{\mathrm{PSV}} &= M_{<} + \mathrm{Att} + b_1 M_{<>} + b_2^{(1)} S^{(1)} + b_2^{(2)} S^{(2)} + b_3 v + b_4 + b_5 M_{<>}^2 \\
&\quad + b_6^{(1)} S_L^{(1)} \\
M_{<} &= \min(M, M_{\max}) \\
\text{where } M_{\max} &= \frac{-(1+b_1)}{2b_5} \\
M_{<>} &= \max(M_{<}, M_{\min}) \\
\text{where } M_{\min} &= \frac{-b_1}{2b_5} \\
\mathrm{Att} &= \begin{cases} A_0 \log_{10}\Delta & \text{for } R \leq R_0 \\ A_0 \log_{10}\Delta_0 - \frac{(R-R_0)}{200} & \text{for } R > R_0 \end{cases} \\
\text{with: } A_0 &= \begin{cases} -0.761 & \text{for } T \geq 1.8\,\mathrm{s} \\ -0.831 + 0.313\log_{10} T - 0.161(\log_{10} T)^2 & \text{for } T < 1.8\,\mathrm{s} \end{cases} \\
\Delta &= S\left[\ln\left(\frac{R^2+H^2+S^2}{R^2+H^2+S_0^2}\right)\right]^{-\frac{1}{2}} \\
\Delta_0 &= \Delta(R_0) \\
\text{where } R_0 &= \frac{1}{2}\left\{\frac{-200A_0(1-S_0^2/S^2)}{\ln 10} + \left[\left[\frac{200A_0(1-S_0^2/S^2)}{\ln 10}\right]^2 - 4H^2\right]\right\}
\end{aligned}
$$

  where Δ is 'representative' distance, S is 'size' of fault, S_0 is coherence radius of source and v is component orientation ($v = 0$ for horizontal, $v = 1$ for vertical).

- Response parameter is pseudo-velocity for $0, 2, 5, 10$ and 20% damping.
- Consider three geological site conditions:

$s = 0$ Sediment: $\Rightarrow S^{(1)} = 0, S^{(2)} = 0$, 151 records.

$s = 1$ Intermediate sites: $\Rightarrow S^{(1)} = 1, S^{(2)} = 0$, 106 records.

$s = 2$ Basement rock: $\Rightarrow S^{(1)} = 0, S^{(2)} = 1$, 54 records.

- Consider three local site categories but only retain two:

$s_L = 0$ Rock: $\Rightarrow S_L^{(1)} = 0$, 100 records.

$s_L = 1$ Stiff soil: $\Rightarrow S_L^{(1)} = 1$, 205 records.

- Cannot include those records from deep soil sites ($s_L = 2$) because only six records.
- Most earthquakes are shallow, depth $H < 25\,\mathrm{km}$.
- Most records have epicentral distances, $R < 50\,\mathrm{km}$.
- Most have magnitudes between 3 and 6.
- Only use records with high signal-to-noise ratio. Quality of records is not adequate for response spectrum calculation outside range 0.04 to $2\,\mathrm{s}$.
- Analysis performed using residue 2-step method. In first step use only records from $M \geq 4.25$ to force a concave form to magnitude scaling (if all records used then find a convex parabola), s_L parameter is not included. In second step find s_L dependence from residuals of first stage including all magnitudes.
- Give expressions to describe distribution of residuals so that can find confidence limits, unlike normal standard deviation based method, see Trifunac (1980).
- Note difference between western USA and Yugoslavian ground motions.

4.62 Mohammadioun (1994a)

- Ground-motion model is:

$$\log \mathrm{SR}(f) = k(f) + \alpha(f)M + n(f)\log R$$

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Uses records from rock sites ($V_s \geq 750\,\mathrm{m/s}$).
- Half of records from $R < 30\,\mathrm{km}$ and significant number from $R < 10\,\mathrm{km}$.
- Most (82%) records from earthquakes with $6.2 \leq M \leq 7.0$.
- Coefficients not given, only results.

4.63 Mohammadioun (1994b)

- Ground-motion model is:

$$\log V(f) = k(f) + \alpha(f)M + n(f)\log R$$

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Choose W. USA to make data as homogeneous as possible in terms of seismotectonic context and parameter quality.

- Notes recording site-intensities may only be average intensity values, thereby neglecting possible microzoning effects.
- Uses M_L because generally available and uniformly determined. Notes may not be best choice.
- Records from free-field and typical of different intensity classes.
- Does regression for records associated with three different intensities: V (184 records, $5.5 \lesssim R \lesssim 200\,\mathrm{km}$), VI (256 records, $3 \lesssim R \lesssim 250\,\mathrm{km}$, VII (274 records, $1 \lesssim R \lesssim 150\,\mathrm{km}$) and four different intensity groups: V-VI, VI-VII, VII and more (extra 25 records, $1 \lesssim R \lesssim 100\,\mathrm{km}$) and V and less (extra 30 records, $25 \lesssim R \lesssim 350\,\mathrm{km}$.
- Graph of $\alpha(f)$ given for horizontal component for the four intensity groups and graph of $n(f)$ for vertical component for intensity VI.

4.64 Musson *et al.* (1994)

- See section 2.108.
- Response parameter is pseudo-velocity for 5% damping.
- More data because use analogue records as well.

4.65 Theodulidis & Papazachos (1994)

- Use same data, equation and procedure as Theodulidis & Papazachos (1992), see Section 2.92.
- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Note lack of near-field data ($R < 20\,\mathrm{km}$, $M > 6.2$) to constrain R_0.
- Only give graphs of original coefficients but give table of smoothed (using a ($\frac{1}{4}$+$\frac{1}{2}$+$\frac{1}{4}$ running average along $\log T$) coefficients for 13 periods and all 5 damping levels.
- Note large residuals for $T > 0.5\,\mathrm{s}$ due mainly to different digitising and processing procedures which significantly affect long period spectral values.
- Check histograms of residuals for 0.1, 0.3, 0.5, 1, 3 and $5\,\mathrm{s}$ and find similar to normal distribution.
- Note no data from $R < 30\,\mathrm{km}$ for $M > 6.5$ so state caution is required for use of equations in that range. Also suggest do not use equations for $M > 7.5$ or for $R > 130\,\mathrm{km}$.
- Note may not apply for very soft soils.
- Note lack of data.

4.66 Dahle *et al.* (1995)

- See Section 2.114.
- Derive spectral attenuation relations for almost double number of periods given. Coefficients smoothed using a third degree polynomial.

4.67 Lee & Trifunac (1995)

- Based on Lee *et al.* (1995). See Section 2.115.
- Response parameter is pseudo-velocity for 5% damping (also use 0, 2, 10 and 20% damping but do not report results).
- Before regression, smooth the actual response spectral amplitudes along the $\log_{10} T$ axis to remove the oscillatory ('erratic') nature of spectra.
- State that for small earthquakes ($M \approx 3$) equations only valid up to about $1\,\mathrm{s}$ because recorded spectra are smaller than recording noise for longer periods.
- Only give coefficients for 0.04, 0.06, 0.10, 0.17, 0.28, 0.42, 0.70, 1.10, 1.90, 3.20, 4.80 and $8.00\,\mathrm{s}$ but give graphs for rest.
- Assume that distribution of residuals from last step can be described by probability function:

$$p(\epsilon, T) = [1 - \exp(-\exp(\alpha(T) + \beta(T)))]^{n(T)}$$

  where $p(\epsilon, T)$ is probability that $\log \mathrm{PSV}(T) - \log \widehat{\mathrm{PSV}}(T) \leq \epsilon(T)$, $n(T) = \min[10, [25/T]]$, $[25/T]$ is integral part of $25/T$. Arrange residuals in increasing order and assign an 'actual' probability of no exceedance, $p^*(\epsilon, T)$ depending on its relative order. Estimate $\alpha(T)$ and $\beta(T)$ by least-squares fit of $\ln(-\ln(1 - p^{1/n(T)})) = \alpha(T)\epsilon(T) + \beta(T)$. Test quality of fit between $\hat{p}(\epsilon, T)$ and $p^*(\epsilon, T)$ by χ^2 and Kolmogorov-Smirnov tests. For some periods the χ^2 test rejects the fit at the 95% level but the Kolmogorov-Smirnov test accepts it.

4.68 Ambraseys *et al.* (1996) & Simpson (1996)

- See Section 2.119.
- Response parameter is acceleration for 5% damping.
- Do no smoothing because if plotted on a normal scale then smoothing should be done on T, but if on log-log plot then smoothing should be done on $\log T$.

4.69 Ambraseys & Simpson (1996) & Simpson (1996)

- See Section 2.120.
- Response parameter is acceleration for 5% damping.

4.70 Bommer *et al.* (1996)

- See section 2.122.
- Response parameter is pseudo-velocity for unspecified damping.

4.71 Crouse & McGuire (1996)

- See section 2.123.
- Response parameter is pseudo-velocity for 5% damping.
- Find k_1 not significantly different than 1 for $T \leq 0.15\,\mathrm{s}$ and k_2 not significantly different than 1 for $T \leq 0.50\,\mathrm{s}$.

4.72 Free (1996) & Free *et al.* (1998)

- See Section 2.124.
- Response parameter is acceleration for 5% damping.
- Finds including focal depth, h, explicitly has dramatic effect on predicted spectra at short distances but insignificant effect at large distances.
- Repeats analysis using only E. N. American data. Finds significantly larger amplitudes than predictions from combined set for short and intermediate distances for periods $> 0.3\,\mathrm{s}$ but similar spectra for large distances.

4.73 Molas & Yamazaki (1996)

- Based on Molas & Yamazaki (1995), see Section 2.88 of Douglas (2001a).
- Response parameters are absolute acceleration and relative velocity for 5% damping.

4.74 Ohno *et al.* (1996)

- See Section 2.126.
- Response parameter is acceleration for 5% damping.
- Plot amplitude factors from first stage against M_w; find well represented by linear function.
- Do not give table of coefficients only graphs of coefficients.

4.75 Sabetta & Pugliese (1996)

- Ground-motion model used is:

$$\log_{10} Y = a + bM - \log_{10}\sqrt{d^2 + h^2} + e_1 S_1 + e_2 S_2$$

- Response parameter, Y, is pseudo-velocity for 5% damping
- Use data from Sabetta & Pugliese (1987).
- Remove anelastic decay term because it was not significant at $\alpha = 0.1$ and sometimes it was positive. Originally geometrical decay coefficient c was allowed to vary but find it is close to -1 so constrain.
- Use three site categories:

$S_1 = 1, S_2 = 0$ Shallow: depth $H \leq 20\,\mathrm{m}$ alluvium $400 \leq V_s \leq 800\,\mathrm{m/s}$.

$S_1 = 0, S_2 = 1$ Deep: depth $H > 20\,\mathrm{m}$ alluvium $400 \leq V_s \leq 800\,\mathrm{m/s}$.

$S_1 = 0, S_2 = 0$ Stiff: $V_s > 800\,\mathrm{m/s}$.

- Accelerograms digitised at 400 samples/sec. Bandpass frequencies chosen by an analysis of signal and fixed trace Fourier spectra. $f_{\min}$ between 0.2 and $0.7\,\mathrm{Hz}$ most about $0.3\,\mathrm{Hz}$ and $f_{\max}$ between 20 and $35\,\mathrm{Hz}$ most about $25\,\mathrm{Hz}$. Instrument correction applied.
- Use one-stage method although two-stage method yields similar results.
- Also present smoothed coefficients.

4.76 Spudich *et al.* (1996) & Spudich *et al.* (1997)

- See Section 2.130
- Response parameter is pseudo-velocity for 5% damping.
- Only use spectral values within the passband of the filter used to correct records hence number of records used for each period varies, lowest number is 99 for periods between 1.7 and $2.0\,\mathrm{s}$.
- Smooth coefficients using cubics or quadratics.

4.77 Abrahamson & Silva (1997)

- Ground-motion model is[4]:

$$\begin{aligned}
\ln \mathrm{Sa} &= f_1 + F f_3 + HW f_{HW}(M) f_{HW}(R_{\mathrm{rup}}) + S f_5 \\
f_1 &= \begin{cases} a_1 + a_2(M - c_1) + a_{12}(8.5 - M)^n + [a_3 + a_{13}(M - c_1)] \ln R \\ \qquad \text{for} \quad M \leq c_1 \\ a_1 + a_4(M - c_1) + a_{12}(8.5 - M)^n + [a_3 + a_{13}(M - c_1)] \ln R \\ \qquad \text{for} \quad M > c_1 \end{cases} \\
\text{where } R &= \sqrt{r_{\mathrm{rup}} + c_4^2} \\
f_3 &= \begin{cases} a_5 & \text{for} \quad M \leq 5.8 \\ a_5 + \frac{a_6 - a_5}{c_1 - 5.8}(M - 5.8) & \text{for} \quad 5.8 < M < c_1 \\ a_6 & \text{for} \quad M \geq c_1 \end{cases} \\
f_{HW}(M) &= \begin{cases} 0 & \text{for} \quad M \leq 5.5 \\ M - 5.5 & \text{for} \quad 5.5 < M < 6.5 \\ 1 & \text{for} \quad M \geq 6.5 \end{cases} \\
f_{HW}(r_{\mathrm{rup}}) &= \begin{cases} 0 & \text{for} \quad r_{\mathrm{rup}} < 4 \\ a_9 \frac{r_{\mathrm{rup}} - 4}{4} & \text{for} \quad 4 < r_{\mathrm{rup}} < 8 \\ a_9 & \text{for} \quad 8 < r_{\mathrm{rup}} < 18 \\ a_9 \left(1 - \frac{r_{\mathrm{rup}} - 18}{7}\right) & \text{for} \quad 18 < r_{\mathrm{rup}} < 24 \\ 0 & \text{for} \quad r_{\mathrm{rup}} > 25 \end{cases} \\
f_5 &= a_{10} + a_{11} \ln(\widehat{\mathrm{PGA}} + c_5)
\end{aligned}$$

  where $\widehat{\mathrm{PGA}}$ is expected peak acceleration on rock as predicted by the attenuation equation with $S = 0$.

- Response parameter is acceleration for unspecified[5] damping.

- Use two site categories:

$S = 0$ Rock: rock ($V_s > 600\,\mathrm{m/s}$), very thin soil ($< 5\,\mathrm{m}$) over rock or soil 5 to $20\,\mathrm{m}$ thick over rock.

$S = 1$ Deep soil: deep soil in narrow canyon (soil $> 20\,\mathrm{m}$ thick and canyon $< 2\,\mathrm{km}$ wide) or deep soil in broad canyon (soil $> 20\,\mathrm{m}$ thick and canyon $> 2\,\mathrm{km}$ wide).

- All records reprocessed using common procedure. Interpolated to 400 samples/sec, low-pass filtering with corner frequency selected for each record based on visual examination of Fourier amplitude spectrum, instrument corrected, decimated to 100 to 200 samples/sec depending on low-pass corner frequency, baseline correction using 0 to 10 degree polynomial, high-pass filtered based on integrated displacements.

- Only use response spectral data within frequency band $1.25 f_h$ to $0.8 f_l$ to avoid effects of filter roll-off. Hence number of records used for regression at each period varies, minimum number is less than 100 records for $0.01\,\mathrm{s}$.

- Well distributed dataset in terms of magnitude and distance.

[4] f_3 given in Abrahamson & Silva (1997) was modified to ensure homogeneity and a linear variation in f_3 with magnitude.

[5] It is probably 5%.

- Supplement data with records from Gazli, Friuli, Tabas, Taiwan, Nahanni and Spitak.
- Consider source mechanism: reverse $\Rightarrow F = 1$, reverse/oblique $\Rightarrow F = 0.5$, others (strike-slip and normal) $\Rightarrow F = 0$).
- Consider hanging wall effect: if over hanging wall $HW = 1$, otherwise $HW = 0$.
- Note that interpretation of c_4 is not clear for their distance measure but yields better fit.
- Model nonlinear soil response by f_5.
- Model uncertainty as magnitude dependent.
- Fix some coefficients to be independent of period so that response spectral values vary smoothly with distance, magnitude and period.
- Smooth coefficients using piecewise continuous linear fits on log period axis. For highly correlated coefficients, smooth one coefficient and re-estimate other coefficients.

4.78 Atkinson (1997)

- Ground-motion model used is:

$$\begin{aligned}\log \mathrm{PSA} &= c_0 + c_1(M_w - 6) + c_2(M_w - 6)^2 + c_3 h - c_{a_1} \log R - c_{a_2} R + c_s S \\ \text{with: } c_{a_2} &= c_{a_3} + c_{a_4} h\end{aligned}$$

- Response parameter is pseudo-acceleration for 5% damping.
- Uses two site categories (no soil profiles were available for Cascadia region):

$S = 0$ Rock: average V_s assumed to be about $2000\,\mathrm{m/s}$

$S = 1$ Soil: average V_s assumed to be about $255\,\mathrm{m/s}$ (although includes some soft soil sites with average V_s about $125\,\mathrm{m/s}$).

- Tectonic type of earthquakes used: crustal, subcrustal and subduction
- Most Cascadia data is from seismograms. Converts vertical measurements from these to one horizontal component.
- Supplements in large magnitude range ($6.7 < M_w \leq 8.2$) with data from 9 subduction earthquakes in Alaska, Mexico, Japan and Chile
- Most magnitudes below 5.3 and no data between 6.8 and 7.5.
- Focal depths between 1 and $60\,\mathrm{km}$
- Only uses events recorded at 3 or more stations. Improves ability of regression to distinguish between magnitude and distance dependencies in data.
- Most low magnitude events were recorded on rock and most high magnitude events were on soil. Thus to stabilize regression takes the coefficients c_s from Boore *et al.* (1994a) and not derived from this data.

- Magnitude partitioning, in first step, into 0.5 unit intervals gave evidence for magnitude dependent attenuation. Uses $c_{a_1} = 1$ for $4.1 \leq M_w \leq 6.7$ and $c_{a_1} = 0.5$ (largest which yielded positive c_{a_2}) for $M_w \geq 7.5$. Thought to show breakdown of point source assumption.
- Demonstrates depth dependence in anelastic decay by performing regression in four $15\,\mathrm{km}$ deep subsets for range $4.1 \leq M_w \leq 6.7$. c_{a_3} and c_{a_4} then finds by regression for each period. No depth dependence for $M_w \geq 7.5$ because of lack of different depths.
- Includes depth dependence in second step because gave better fit for short periods.
- Checks dependence on crustal, interface and intra-slab events; finds no dependence.

4.79 Campbell (1997), Campbell (2000) & Campbell (2001)

- See Section 2.132
- Ground-motion model (horizontal component) is:

$$\begin{aligned}\ln \mathrm{SA}_H &= \ln A_H + c_1 + c_2 \tanh[c_3(M-4.7)] + (c_4 + c_5 M) R_{\mathrm{SEIS}} + 0.5 c_6 S_{\mathrm{SR}} \\ &\quad + c_6 S_{\mathrm{HR}} + c_7 \tanh(c_8 D)(1 - S_{\mathrm{HR}}) + f_{\mathrm{SA}} \\ f_{\mathrm{SA}} &= \begin{cases} 0 & \text{for} \quad D \geq 1\,\mathrm{km} \\ c_6(1-S_{\mathrm{HR}})(1-D)(1-0.5 S_{\mathrm{SR}}) & \text{for} \quad D < 1\,\mathrm{km} \end{cases}\end{aligned}$$

- Ground-motion model (vertical component) is:

$$\begin{aligned}\ln \mathrm{SA}_V &= \ln \mathrm{SA}_H + c_1 + b_2 M + c_2 \tanh[d_1(M-4.7)] + c_3 \tanh[d_2(M-4.7)] \\ &\quad + b_3 \ln[R_{\mathrm{SEIS}} + b_4 \exp(b_5 M)] + b_6 \ln[R_{\mathrm{SEIS}} + b_7 \exp(b_8 M)] + b_9 F \\ &\quad + [c_4 \tanh(d_3 D) + c_5 \tanh(d_4 D)](1 - S_{\mathrm{SR}})\end{aligned}$$

- Response parameter is pseudo-acceleration for 5% damping.
- Notes importance of depth to basement rock, D, for modelling long period site response. For shallow sediments defines D as depth to top of Cretaceous or older deposits, for deep sediments determine D from crustal velocity profiles where define basement as crystalline basement rock or sedimentary deposits having a P-wave velocity $\geq 5\,\mathrm{km/s}$ or shear-wave velocity $\geq 3\,\mathrm{km/s}$ (called 'seismic basement' by geophysicists).
- Uses different data than for PGA equations hence: reverse (3), thrust (H:9, V:6), reverse-oblique (2) and thrust-oblique (0), total (H:14, V:11) (H:140 records, V:85 records), strike-slip (H:124 records, V:88 records). Only two normal faulting earthquakes in horizontal set of records (contributing 2 records) so a difference in not modelled although $F = 0.5$ is given as first approximation (later revised to $F = 0$) to use as for PGA case.
- Only excludes records from toe and base of dams, included those from buildings and bridge columns which were excluded from PGA study, because of lack of data.
- Uses weighted regression analysis. Assigns recordings from a given earthquake that fell within the same distance interval (ten logarithmical spaced) same weight as those recordings from other earthquakes that fell within the same distance interval. Gives recordings from a given earthquake that occurred at the same site location the same cumulative weight as a single recording at that distance, thus reducing the bias.

- Performs analysis on spectral ratio $\ln(\mathrm{PSA}/\mathrm{PGA})$ because of unacceptably large period-to-period variability in regression coefficients when direct regression is applied and strongly correlated coefficients. Notes that are too many regression coefficients so it was necessary to perform analysis in many steps, at each step different coefficients are determined and detrended and residuals examined to find appropriate functional forms for trends present. Yields more stable results.
- No consideration of nontriggering instruments made, unlike PGA study.

4.80 Schmidt *et al.* (1997)

- See Section 2.136.
- Response parameter is pseudo-velocity for 5% damping.

4.81 Youngs *et al.* (1997)

- See Section 2.137.
- Ground-motion model used is:

$$\ln(\mathrm{SA}/\mathrm{PGA}) = B_1 + B_2(10 - \mathbf{M})^3 + B_3 \ln\left[r_{\mathrm{rup}} + \mathrm{e}^{\alpha_1 + \alpha_2 \mathbf{M}}\right]$$

  where α_1 and α_2 are set equal to C_4 and C_5 of appropriate PGA equation.
- Response parameter, SA, is acceleration for 5% damping.
- Do analysis on response spectral amplification because digitised and processed accelerograms used for spectral attenuation is only a subset of PGA database and they are often those with strongest shaking. Hence analysis directly on spectral accelerations may be biased.
- Smooth coefficients.

4.82 Bommer *et al.* (1998)

- Ground-motion model is:

$$\begin{aligned}\log(\mathrm{SD}) &= C_1 + C_2 M + C_4 \log r + C_A S_A + C_S S_S \\ r &= \sqrt{d^2 + h_0^2}\end{aligned}$$

- Response parameter is displacement for $5, 10, 15, 20, 25$ and 30% damping.
- Use three site conditions:

  R Rock: $V_s > 750\,\mathrm{m/s}$, $S_A = 0$, $S_S = 0$, 30–45 records.

  A Stiff soil: $360 < V_s \leq 750\,\mathrm{m/s}$, $S_A = 1$, $S_S = 0$, 56–92 records.

  S Soft soil: $180 < V_s \leq 360\,\mathrm{m/s}$, $S_A = 0$, $S_S = 1$, 32–43 records.

- Use subset of data of Ambraseys *et al.* (1996) (see 2.119) data with a few changes and exclusion of records from earthquakes with $M_s < 5.5$ because ground motion at long periods was of interest and to increase likelihood of acceptable single-to-noise ratio at longer periods.

- Each record individually filtered. Firstly filter record with sharp low cut-off at $0.1\,\mathrm{Hz}$ and plot velocity and displacement time-histories. Check, visually, whether contaminated by noise and if so increase cutoff frequency by small amount and repeat procedure until resulting velocity and displacement time-histories are deemed acceptable and no significant improvement is observed by further increase of cutoff frequency. Instrument correction not applied because high frequency distortion caused by transducer characteristics not important for displacement spectra. Only use each record for regression for periods up to $0.1\,\mathrm{s}$ less than filter cutoff used for that record to avoid distortion by filter, hence as period increases number of data points decreases.

- Regression procedure same as Ambraseys *et al.* (1996), see 2.119.

4.83 Perea & Sordo (1998)

- Ground-motion model is:

$$\ln \mathrm{Pa} = \beta_1 + \beta_2 M + \beta_3 \ln(R + 25)$$

- Response parameter is pseudo-acceleration for 5% damping.

- All records from five medium soft soil sites.

- Use m_b for $M < 6$ and M_s otherwise, because m_b is more representative of released energy for small earthquakes and M_s better represents energy release for large earthquakes because m_b saturates starting from $M > 6$.

- Try including anelastic decay term, $\beta_4 R$ but it does not significantly affect standard deviation.

- Also repeat analysis for three other zones. Zone 1: 3 earthquakes, 3 records ($5.0 \leq M \leq 6.4$, $80 \leq R \leq 156\,\mathrm{km}$) for which conclude has too limited data for reliable equation. Zone 3[6]: 11 earthquakes, 13 records ($4.5 \leq M \leq 7.7$, $251 \leq R \leq 426\,\mathrm{km}$) for which find fits spectra of medium sized shocks better than large shocks because of lack of data for large earthquakes. Zone 4: 4 earthquakes, 7 records ($5.1 \leq M \leq 6.2$, $356 \leq R \leq 573\,\mathrm{km}$) for which find β_2 is negative and β_3 is positive for some periods (which is nonphysical) which state is due to limited number of earthquakes and their similar epicentral distances.

- Find fit spectra of medium sized earthquakes than large earthquakes because of lack of data from large earthquakes.

- Only give graphs of coefficients.

[6]The following values are from their Table 1 which does not match with their Figure 3.

4.84 Reyes (1998)

- See Section 2.143.
- Response parameter is acceleration for 5% damping.

4.85 Shabestari & Yamazaki (1998)

- Ground-motion model is:

$$\log y(T) = b_0(T) + b_1(T)M + b_2(T) - \log r + b_4(T)h + c_i(T)$$

  where $c_i(T)$ is the station coefficient, reflecting relative site effect for each period, assuming zero mean for all stations.

- Response parameters are acceleration and velocity for 5% damping.
- Include at least five earthquakes with $M_{\mathrm{JMA}} \geq 7.2$.
- Exclude earthquakes with focal depths, h, equal to $0\,\mathrm{km}$ or greater than $200\,\mathrm{km}$.
- Exclude records with vectorial composition of PGA less than $0.01\,\mathrm{m/s^2}$.
- Use three-stage iterative partial regression method.
- For $T \geq 6\,\mathrm{s}$ constrain horizontal anelastic coefficient to zero because get positive coefficient.
- See Yamazaki *et al.* (2000) for examination of station coefficients.

4.86 Chapman (1999)

- See Section 2.150.
- Response parameter is pseudo-velocity for 2, 5 and 10% damping.

4.87 Spudich *et al.* (1999) & Spudich & Boore (2005)

- See Section 2.154.
- Response parameter is pseudo-velocity for 5% damping.
- Use only use response spectral data within frequency band $1.25f_h$ to $0.75f_l$ to avoid effects of filter roll-off. Eight records were not processed like the rest so use only response spectral values within 0.1 to $1\,\mathrm{s}$. Hence number of records used for regression at each period varies, minimum number used is 105 records for $2\,\mathrm{s}$.
- Give smoothed coefficients using cubic function.

4.88 Ambraseys & Douglas (2000), Douglas (2001b) & Ambraseys & Douglas (2003)

- See Section 2.157.
- Response parameter is acceleration for 5% damping.
- Find b_2 and b_3 significantly different than 0 at 5% level for all periods but b_A and b_S not significant for many periods (especially for vertical component).
- Find deamplification for vertical component on soft and stiff soil compared with rock. Check by removing all 34 Northridge records (many of which were on soft soil) and repeat analysis; find little change.
- Also derive equations for horizontal response under influence of vertical acceleration using a bending SDOF model; find little change in response.

4.89 Bozorgnia *et al.* (2000)

- See Section 2.158.
- Response parameter is acceleration for 5% damping.
- Different set of data than for PGA hence: strike-slip: 20 earthquakes (including one normal faulting shock), reverse: 7 earthquakes and thrust: 6 earthquakes.
- Find considerable period-to-period variability in coefficients causing predicted spectra to be very jagged near limits of magnitude and distance ranges so carried out partial smoothing of coefficients.

4.90 Campbell & Bozorgnia (2000)

- See Section 2.159.
- Response parameter is pseudo-acceleration for 5% damping.

4.91 Chou & Uang (2000)

- Ground-motion model is:

$$\log Y = a + b(M-6) + c(M-6)^2 + d\log(D^2+h^2)^{1/2} + eG_c + fG_d$$

- Response parameter is pseudo-velocity for 5% damping.
- Use three site categories (based on average shear-wave velocity, V_s, over top $30\,\mathrm{m}$):

Classes A+B Hard rock or rock: $V_s > 760\,\mathrm{m/s}$, $G_c = 0$, $G_d = 0$, 35 records.

Class C Very dense soil and soft rock: $360 < V_s \leq 760\,\mathrm{m/s}$, $G_c = 1$, $G_d = 0$, 97 records.

Class D Stiff soil: $180 \leq V_s \leq 360\,\mathrm{m/s}$, $G_c = 0$, $G_d = 1$, 141 records.

- Records from free-field or ground level of structures no more than two storeys in height.

- Smooth coefficients using cubic polynomial.
- Do not give coefficients for all periods.
- Find cannot use equation to predict near-field ground motions.

4.92 Field (2000)

- See Section 2.160.
- Distribution w.r.t. site class for $3.0\,\mathrm{s}$ is: B, 10 records; BC, 27 records; C, 13 records; CD, 119 records; D, 187 records; DE, 1 record.
- Response parameter is acceleration for 5% damping.
- Constrains b_3 for 1.0 and $3.0\,\mathrm{s}$ to zero because originally finds positive value.
- 151 records have basin-depth estimates.
- Does not find significant slopes for residuals w.r.t. predicted ground motion at BC sites.
- Plots squared residuals w.r.t. V_s and finds small significant trends for 1.0 and $3.0\,\mathrm{s}$.

4.93 Kawano *et al.* (2000)

- Ground-motion model is:

  $$\log S_i(T) = a(T)M - \{b(T)X_{eq} + \log X_{eq}\} + c_i(T)$$

  where $c_i(T)$ is an individual site amplification factor for each of 12 stations.
- Response parameter is acceleration for 5% damping.
- Focal depths between 0 and $60\,\mathrm{km}$.
- Use data either recorded at ground surface where $0.5 \leq V_s \leq 2.7\,\mathrm{km/s}$ ($1.7 \leq V_p \leq 5.5\,\mathrm{km/s}$) or obtained by analytically removing effects of uppermost surface layers of ground from underground observation data (or by stripping-off analysis) using underground structure.
- Use only ground motion after arrival of first S wave because most important for aseismic design.
- Do not give table of coefficients, only graphs of coefficients.
- Define amplification factors, $d_i(T) = c_i(T) - c_0(T)$ for horizontal motion and $d_i(T) = c_{v,i}(T) - c_0(T)$ for vertical motion, where $c_0(T)$ is the regression coefficient for data observed at ground layer equivalent to seismic bedrock.
- Find $S_h(T) = S_b(T)\alpha_h(T)\beta_h(T)$ where $S_b(T)$ is $S_0(T)$. $\alpha_h(T) = (V_s/V_{s,b})^{-\delta_h(T)}$ for $T \leq T_{s,1}$ and $\alpha_h(T) = \alpha_h(T_{s,1})$ for $T > T_{s,1}$ where $T_{s,1}$ is the primary predominant period of surface layer. $\beta_h(T) = 1$ for $T \leq T_{s,1}$, $\beta_h(T) = (T/T_{s,1})^{-\log(\alpha_h(T_{s,1}))}$ for $10T_{s,1} > T > T_{s,1}$ and $\beta_h(T) = 10^{-\log(\alpha_h(T_{s,1}))}$ for $T \geq 10T_{s,1}$. $V_{s,b} = 2.2\,\mathrm{km/s}$. Similar relationships are defined for vertical motion, $S_v(T)$.
- Note that relation does not include effect of source mechanism or rupture propagation, so probably less valid in near-fault region.

4.94 Kobayashi *et al.* (2000)

- See Section 2.162.
- Response parameter is pseudo-velocity for 5% damping.
- Use significantly less records for $T > 1.5\,\mathrm{s}$.

4.95 McVerry *et al.* (2000)

- Ground-motion model for crustal earthquakes is (using form from Abrahamson & Silva (1997), see Section 4.77):

$$\begin{aligned}\ln \mathrm{SA}'(T) &= C_1(T) + C_{4AS}(M-6) + C_{3AS}(T)(8.5-M)^2 + C_5(T)r \\ &+ (C_8(T) + C_{6AS}(M-6))\ln(r^2 + C_{10AS}^2(T))^{1/2} + C_{46}(T)r_{\mathrm{VOL}} \\ &+ \{C_2(T)r + C_{44}(T) + (C_9(T) + C_7(T)(M-6))(\ln(r^2 + C_{10AS}^2(T))^{1/2} \\ &- \ln C_{10AS})\} \\ &+ \{C_{29}(T)\} \\ &+ \{C_{30AS}(T)\ln(\mathrm{PGA}'_{WA} + 0.03) + C_{43}(T)\} \\ &+ C_{32}\mathrm{CN} + C_{33AS}(T)\mathrm{CR}\end{aligned}$$

  Also add on hanging wall term, see Section 4.77. Subscript AS denotes those coefficients from Abrahamson & Silva (1997). Three parts of equation within $\{\ldots\}$ are for site conditions MA/SA, Class B and Class C respectively. PGA'_{WA} is the predicted PGA ($\mathrm{SA}'(0)$) for weak rock category. $\mathrm{CN} = -1$ for normal mechanism and 0 otherwise. $\mathrm{CR} = 0.5$ for reverse/oblique, 1.0 for reverse and 0 otherwise. Ground-motion model for subduction zone earthquakes is (using form from Youngs *et al.* (1997), see Section 4.81):

$$\begin{aligned}\ln \mathrm{SA}'(T) &= C_{11}(T) + [C_{12Y} + (C_{17Y}(T) - C_{17}(T))C_{19Y}] \\ &+ C_{13Y}(T)(10-M)^3 + C_{17}(T)\ln(r + C_{18Y}\exp(C_{19Y}M)) + C_{20}(T)H_C \\ &+ C_{24}(T)\mathrm{SI} + C_{46}(T)r_{\mathrm{VOL}}(1-\mathrm{DS}) \\ &+ \{C_{44}(T) + C_{16}(T)(\ln(r + C_{18Y}\exp(C_{19Y}M)) \\ &- \ln(C_{18Y}\exp(C_{19Y}M)))\} \\ &+ \{C_{29}(T)\} \\ &+ \{C_{30Y}(T)\ln(\mathrm{PGA}'_{WA} + 0.03) + C_{43}(T)\}\end{aligned}$$

  Subscript Y denotes those coefficients from Youngs *et al.* (1997). Three parts of equation within $\{\ldots\}$ are for site conditions MA/SA, Class B and Class C respectively. $\mathrm{SI} = 1$ for subduction interface and 0 otherwise. $\mathrm{DS} = 1$ for deep slab and 0 otherwise. r_{VOL} is length of path that lies in the volcanic zone.

- Response parameter is acceleration for 5% damping.
- Use four site conditions (mostly based on geological descriptions rather than measured shear-wave velocity):

  WA Weak rock sites, or sites with soil layer of thickness $\leq 3\,\mathrm{m}$ overlying weak rock.

MA/SA Moderate-strength or strong rock sites, or sites with soil layer of thickness $\leq 3\,\mathrm{m}$ overlying moderate-strength or strong rock.

Class B Intermediate soil sites or sites with soil layer of thickness $> 3\,\mathrm{m}$ overlying rock.

Class C Flexible or deep soil sites with natural periods $> 0.6\,\mathrm{s}$.

Justify soil categories using statistical studies of residuals at early stage. Exclude response spectra from very soft soil sites ($V_s < 150\,\mathrm{m/s}$ for depths of $\gtrsim 10\,\mathrm{m}$).

- Use data for PGA equation from Zhao *et al.* (1997), see Section 2.138.
- Exclude records from bases of buildings with >4 storeys.
- Use less records for long periods because noise.
- Lack of data prevent development of robust model purely from NZ data. Plot residuals of predicted response using published attenuation relations (base models) for other areas to find relations which gave good representations of NZ data. Then modify some coefficients to improve match; imposing constraints so that the selected models control behaviour at short distances where NZ data lacking. Require crustal and subduction zone expressions for rock sites to match magnitude dependence of base models at $r = 0\,\mathrm{km}$. Constrain coefficients that occur nonlinearly and nonlinear site response coefficient for Class C to base model values.
- Find anelastic attenuation term and additive terms for shallow slab earthquakes for subduction earthquakes not statistically significant. Also differences in attenuation rates for shallow slab, deep slab and interface earthquakes not statistically significant.
- Exclude deep slab earthquakes because of high attenuation in mantle; note equation should not be used for such earthquakes.
- Different attenuation rate for site category MA/SA because of magnitude dependence apparent in residuals for simpler model.
- Eliminate nonlinear site response term for Class B because find unacceptable (positive) values of coefficient and constraining to negative values produces poorer fit.
- Predicted PGA ($\mathrm{SA}'(0)$) from response spectrum set of records considerably smaller than those, $\mathrm{SA}(0)$, from the complete PGA set of records. Thus scale $\mathrm{SA}'(T)$ by ratio $\mathrm{SA}(0)/\mathrm{SA}'(0)$.
- Standard error has a magnitude dependent intra-event component and a magnitude independent inter-event component.
- Note lack of data for large magnitude subduction zone earthquakes and large magnitude near source data for crustal earthquakes.
- Do not give coefficients, only predictions.

4.96 Monguilner *et al.* (2000b)

- Ground-motion model is:

$$\log S_A(T) = A(\Delta, T) + M + b_1(T) + b_2(T)M + b_3(T)s + b_4(T)v + b_5(T)M^2 + e_p(i)$$

where $A(\text{DE}, H, S, T) = A_0(T) \log \Delta(\text{DE}, H, M)$, $\Delta = (\text{DE}^2 + H^2 + S^2)^{\frac{1}{2}}$, H is focal depth, p is the confidence level, s is from site classification (details not given in paper) and v is component direction (details not given in paper although probably $v = 0$ for horizontal direction and $v = 1$ for vertical direction).

- Response parameter is pseudo-acceleration for unknown damping level.
- Use same data and weighting method as Monguilner *et al.* (2000a) (see Section 2.163).
- Find $A_0(T)$ by regression of the Fourier amplitude spectra of the strong-motion records.
- Estimate fault area, S, using $\log S = M_s + 8.13 - 0.6667 \log(\sigma \Delta\sigma/\mu)$.
- Equation only valid for $M_{\min} \leq M \leq M_{\max}$ where $M_{\min} = -b_2/(2b_5(T))$ and $M_{\max} = -(1 + b_2(T))/(2b_5(T))$. For $M < M_{\min}$ use M for second term and $M = M_{\min}$ elsewhere. For $M > M_{\max}$ use $M = M_{\max}$ everywhere.
- Examine residuals, $\epsilon(T) = \log S_A(T) - \log S'_A(T)$ where $S'_A(T)$ is the observed pseudo-acceleration and fit to the normal probability distribution, $p(\epsilon, T) = \int \exp[-(x - \mu(T))/\sigma(T)]^2/(\sigma(T)\sqrt{2\pi})$, to find $\mu(T)$ and $\sigma(T)$. Find that the residuals fit the theoretical probably distribution at the 5% level using the χ^2 and KS[7] tests.
- Do not give coefficients, only graphs of coefficients.

4.97 Shabestari & Yamazaki (2000)

- Ground-motion model is:

$$\log y(T) = b_0(T) + b_1(T)M + b_2(T) - \log r + b_4(T)h + c_i(T)$$

  where $c_i(T)$ is the station coefficient, reflecting the relative site effect for each period, assuming zero mean for all stations.

- Response parameters are acceleration and velocity for 5% damping.
- Depths between 1 (includes earthquakes with depths reported as $0\,\text{km}$) and $158\,\text{km}$. Exclude earthquakes with focal depths greater than $200\,\text{km}$.
- Exclude records with vectorial composition of PGA less than $0.01\,\text{m/s}^2$.
- Exclude data from stations which have recorded less than two records, because the station coefficient could not be determined adequately. Use records from 823 stations.
- Most records from distances between 50 and $300\,\text{km}$.
- Use three-stage iterative partial regression method.
- For $T \geq 5\,\text{s}$ constrain horizontal anelastic coefficient to zero because get positive coefficient.

[7] Probably this is Kolmogorov-Smirnov.

4.98 Smit *et al.* (2000)

- See Section 2.165.
- Response parameter is acceleration for 5% damping.

4.99 Takahashi *et al.* (2000)

- See Section 2.166.
- Response parameter is pseudo-velocity for 5% damping.
- For periods $\geq 1\,\mathrm{s}$ long period noise in records leads to reduction in number of records.
- Set b and e to zero at long periods because estimates not statistically significant.
- Find that soft soil site correction terms may be affected by different processing procedures for data from different sources.

4.100 Lussou *et al.* (2001)

- See Section 2.170.
- Response parameter is pseudo-acceleration for 5% damping.

4.101 Das *et al.* (2002)

- Ground-motion model is:

  $$\log[PSV(T)] = c_1(T) + c_2(T)M + c_3(T)h + c_4(T)\log(\sqrt{R^2 + h^2}) + c_5(T)v$$

  where $v = 0$ for horizontal and 1 for vertical.
- Response spectral parameter is pseudo-velocity for 5% damping.
- Use records from stiff soil/rock sites.
- Focal depths between 10 and $100\,\mathrm{km}$.
- Use square-root-of-sum-of-squares (SRSS) to combine horizontal components to reduce strong azimuthal dependence of ground motions. Note that dividing predicted spectra by 1.41 gives spectrum for each component separately.
- Do not derive equations for $T > 1\,\mathrm{s}$ because of baseline problems and noise in accelerograms at longer periods.
- Try more complex functional forms but not enough data to constrain all parameters to physically-realistic values.
- Smooth coefficients using unspecified technique.
- Report residual spectra for different probability levels not σ.

4.102 Gülkan & Kalkan (2002)

- See Section 2.175.
- Response parameter is acceleration for 5% damping.

4.103 Khademi (2002)

- See Section 2.176.
- Response parameter is acceleration for 5% damping.

4.104 Manic (2002)

- Ground-motion model is:

$$\begin{aligned} \log \mathrm{PSV}(T) &= c_1(T) + c_2(T)M + c_3(T)\log(R) + c_4(T)S_A \\ \text{where } R &= (d^2 + d_0^2)^{1/2} \end{aligned}$$

- Response parameter is pseudo-velocity for 5% damping,
- Uses two site categories:

$S_A = 0$ Rock, $V_{s,30} > 750\,\mathrm{m/s}$.

$S_A = 1$ Stiff soil, $360 < V_{s,30} \leq 750\,\mathrm{m/s}$.

Soft soil sites ($V_s \leq 360\,\mathrm{m/s}$) do not exist in set of records.

- Use technique of Ambraseys *et al.* (1996) to find the site coefficient $c_4(T)$, i.e. use residuals from regression without considering site classification.
- Derives separate equations for M_s and M_L and for r_{jb} and r_{epi}.

4.105 Schwarz *et al.* (2002)

- See Section 2.179.
- Response parameter is acceleration for 5% damping.

4.106 Zonno & Montaldo (2002)

- See Section 2.182.
- Response parameter is pseudo-velocity for 5% damping.

4.107 Alarcón (2003)

- See Section 2.183.
- Response parameter is acceleration for 0, 5 and 10% damping but only report coefficients for 5% damping.
- Derive equations for 84[8] periods but only reports coefficients for 11 periods.

4.108 Atkinson & Boore (2003)

- See Section 2.185.
- Response parameter is pseudo-acceleration for 5% damping.

4.109 Berge-Thierry *et al.* (2003)

- Ground-motion model is:

$$\log_{10}\mathrm{PSA}(f) = a(f)M + b(f)d - \log_{10} d + c_1(f) + c_2(f)$$

  where $c_1(f)$ is for rock sites and $c_2(f)$ is for alluvium sites.

- Use two site categories based on V_s where V_s is the average shear-wave velocity in top $30\,\mathrm{m}$:

  1. Rock, $V_s > 800\,\mathrm{m/s}$.
  2. Alluvium, $300 < V_s < 800\,\mathrm{m/s}$.

  Note that some uncertainty in site classification due to lack of V_s values at many stations.

- Response parameter is spectral acceleration for 5%, 7%, 10% and 20% damping.
- Note that not enough data to derive an equation using only French data so had to use European and US data.
- Use only records from earthquakes with focal depth $\leq 30\,\mathrm{km}$ so as to be consistent with shallow crustal earthquakes in France.
- Predominately use corrected data from Ambraseys *et al.* (2000).
- Supplement European data with some data from western USA to improve the magnitude and distance distribution.
- Exclude records from Ambraseys *et al.* (2000) from earthquakes with $M_s < 4$.
- Exclude records from Ambraseys *et al.* (2000) with record lengths $< 10\,\mathrm{s}$.
- Exclude records from Ambraseys *et al.* (2000) with poor visual quality.
- Exclude records from Ambraseys *et al.* (2000) from non-free-field stations or those inside a building on the third floor or higher.

[8]On page 8 of paper it says 88 periods.

- Exclude records from Ambraseys *et al.* (2000) from stations with unknown or very soft soil site conditions.
- Processing procedure of records from Ambraseys *et al.* (2000) is: baseline correct uncorrected record, re-sample record to $0.01\,\mathrm{s}$ time-step and bandpass filtered using a elliptical filter with cut-offs of 0.25 and $25\,\mathrm{Hz}$ because most instruments were SMA-1s with natural frequency of $25\,\mathrm{Hz}$ and damping of 60%. No instrument correction was applied because instrument characteristics are not known.
- Only use US records from earthquakes with $M > 6$.
- Use the already corrected records from USGS and CDMG.
- Most data from rock sites is from earthquakes with $M < 6$.
- 49.7% of data is from Italy and 16.9% is from USA. All other countries contribute less than 10% each.
- Use hypocentral distance because believe it accounts for both point and extended sources.
- Use uniformly calculated M_s for data from Ambraseys *et al.* (2000) and M_w for data from W. USA, which believe is equivalent for M_s for $M_w > 6$.
- Coefficients only reported for horizontal spectral acceleration for 5% damping.
- Note that recent data, e.g. Chi-Chi, shows saturation of ground motions at short distances but data used only contains a few records at close distances so data not sufficient to model such phenomenon.
- Obtain positive $b(f)$ coefficients for periods $> 1s$ which believe is due to low frequency noise and surface waves.
- Believe that small difference between estimated rock and alluvium motions could be due to incorrect site classification at some stations.
- Repeat regression using a randomly selected half of the data. Find very small differences between predicted ground motions using half or complete data set so believe equation is stable.
- Repeat regression excluding data from W. USA and find very small differences between predicted ground motions so believe equation is not influenced by data from W. USA.
- Repeat regression using M_w rather than M_s if available and find that predicted ground motions are different but that the predictions using M_s are higher than those using M_w so note that equation using M_s is conservative hence it is useful in a nuclear safety assessment.
- Repeat regression using r_{rup} rather than r_{hypo} and find that predicted ground motions using r_{hypo} are higher than when r_{rup} is used because using r_{hypo} places source further from source of energy.
- Plot residuals for 0.03 and $2\,\mathrm{s}$ and find not systematic bias in residuals.

4.110 Bommer *et al.* (2003)

- See Section 2.187.
- Response parameter is acceleration for 5% damping.

4.111 Campbell & Bozorgnia (2003d,a,b,c) & Bozorgnia & Campbell (2004b)

- See Section 2.188.
- Response parameter is pseudo-acceleration for 5% damping.
- To make regression analysis more stable set c_2 equal to value from better-constrained regression of uncorrected PGAs.
- Do limited amount of smoothing of regression coefficients to reduce the considerable amount of period-to-period variability in the regression coefficients that caused variability in predicted pseudo-acceleration especially for small distances and large magnitudes.

4.112 Fukushima *et al.* (2003)

- Ground-motion model is:

$$\log \mathrm{Sa}(f) = a(f)M - \log(R + d(f)10^{e(f)M}) + b(f)R + c_1\delta_1 + c_2\delta_2$$

- Use two site categories:
  1. Rock sites with $V_s > 800\,\mathrm{m/s}$. $\delta_1 = 1$ and $\delta_2 = 0$.
  2. Soil sites with $V_s < 800\,\mathrm{m/s}$. $\delta_2 = 1$ and $\delta_1 = 0$.

  Note that some data (Turkish and Japanese) are associated with liquefaction phenomena and so probably $V_s < 300\,\mathrm{m/s}$.
- Choose functional form to include effect of amplitude saturation close to source.
- Note that negative Q values obtained in some ground motion estimation equations may be due to the lack of amplitude saturation terms.
- Do not investigate effect of rupture mechanism, directivity, and the hanging wall effect because of a lack of data.
- Use same set of data as Berge-Thierry *et al.* (2003) but with the addition of records from the 1995 Hyogo-ken Nanbu and 1999 Kocaeli earthquakes, which are used to help constrain the near-source characteristics. In total use 399 records from west Eurasia, 162 from USA, 154 from Hyogo-ken Nanbu and 25 from Kocaeli.
- Remove records from distances greater than the distance at which the predicted PGA is less than $10\,\mathrm{cm/s}^2$ (the average trigger level plus the standard error of observation) as predicted by a previously derived ground motion prediction equation that agrees well with the 1995 Hyogo-ken Nanbu and 1999 Kocaeli earthquakes although they note the process should be iterative.

- Use only records from earthquakes with $M \geq 5.5$ so as to allow the use of a linear magnitude dependence.
- Due to the nonlinear functional form adopt a iterative method to find $d(f)$ and $e(f)$. However, due to the lack of near-source data an accurate value of $e(f)$ cannot be found therefore set $e(f)$ to 0.42, which gives accelerations that agree with the observed peak accelerations in the 1995 Hyogo-ken Nanbu and 1999 Kocaeli earthquakes.
- Bandpass filter records with cut-offs of 0.25 and $25\,\mathrm{Hz}$. Note that due to the presence of many records from analogue instruments the results for frequencies higher than $10\,\mathrm{Hz}$ are less reliable than those for lower frequencies.
- Find that for frequencies $> 0.4\,\mathrm{Hz}$ the $b(f)$ coefficient corresponds to positive Q values. For lower frequencies the value of $b(f)$ correspond to negative Q values, which note could be due to instrumental noise or the effect of surface waves that are not well represented by the functional form adopted.
- Note that the small difference between predicted rock and soil motions may be due to intrinsic rock amplification due to rock weathering or inappropriate site classification for some records (e.g. those from the 1999 Kocaeli earthquake, which are all considered to be on soil).
- Plot residuals with respect to regional origin (Hyogo-ken Nanbu, USA, western Eurasian and Kocaeli) and find no clear bias or trend.
- Note that most of the used near-fault records come from strike-slip earthquakes and so the equation may be only should be used for prediction of strike-slip motions.
- Note that the site classification scheme adopted is very basic but lack information for more sophisticated method.

4.113 Kalkan & Gülkan (2004a)

- See Section 2.197.
- Response parameter is pseudo-acceleration for 5% damping.

4.114 Kalkan & Gülkan (2004b) and Kalkan & Gülkan (2005)

- See Section 2.198.
- Response parameter is pseudo-acceleration for 5% damping.

4.115 Matsumoto *et al.* (2004)

- Ground-motion model is (for r_{rup}):

$$\log SA(T) = C_m(T)M + C_h(T)H_c - C_d(T)\log[R + 0.334\exp(0.653M)] + C_o(T)$$

Ground-motion model is (for r_q):

$$\log SA(T) = C_m(T)M + C_h(T)H_c - C_d(T)X_{\mathrm{eq}} - \log X_{\mathrm{eq}} + C_o(T)$$

$H_c = h$ for $h < 100\,\mathrm{km}$ and $H_c = 100\,\mathrm{km}$ for $h > 100\,\mathrm{km}$.

- Response parameter is acceleration for 5% damping.
- Data from at 91 dam sites with rock foundations. Most instruments in inspection gallery at lowest elevation (for concrete dams) and in bottom inspection gallery (for embankment dams). Note that $1.8 \leq V_p \leq 4.5\,\mathrm{km/s}$ for bedrock of many concrete dams and $1.5 \leq V_p \leq 3.0\,\mathrm{km/s}$ for bedrock of embankment dams, which convert to $0.7 \leq V_s \leq 1.5\,\mathrm{km/s}$.
- Select data from $M > 5$, $d_e < 200\,\mathrm{km}$ and focal depth $h < 130\,\mathrm{km}$.
- Most records from $h < 60\,\mathrm{km}$.
- Most records from $d < 100\,\mathrm{km}$.
- Classify earthquakes into three types:

Shallow crustal Epicentres located inland at shallow depths. 175 records[9].

Inter-plate Epicentres located in ocean with $h < 60\,\mathrm{km}$. 55 records.

Deep intra-slab Epicentres located inland with $h > 60\,\mathrm{km}$. 63 records.

- Know fault source mechanism for 12 earthquakes.
- Adopt $0.334 \exp(0.653M)$ from earlier Japanese study.
- Derive coefficients regardless of earthquake type. Then derive correction factors for each earthquake type.
- Do not report coefficients only graphs of coefficients against period.
- Find good agreement between predicted spectra and observed spectra for two stations that recorded the magnitude 8.0 Tokati-oki 2003 earthquake.

4.116 Özbey *et al.* (2004)

- See Section 2.202.
- Response parameter is acceleration for 5% damping.

4.117 Pankow & Pechmann (2004) and Pankow & Pechmann (2006)

- See Section 2.203.
- Response parameter is pseudo-velocity for 5% damping.

4.118 Sunuwar *et al.* (2004)

- See Section 2.204.
- Response parameter is pseudo-acceleration for 5% damping.
- Developed equations up to $5\,\mathrm{s}$ but do not think results for 4 and $5\,\mathrm{s}$ are satisfactory.

[9] The authors also give number of 'sets' as 81 for shallow crustal, 29 for inter-plate and 29 for deep intra-slab

4.119 Takahashi *et al.* (2004)

- Ground-motion model is:

$$\begin{aligned} \log[y(T)] &= aM - bx - \log r + e(h - h_c)\delta_h + S_R + S_I + S_S + S_k \\ r &= x + c\exp(dM) \end{aligned}$$

  Use S_R only for crustal reverse events, S_I only for interface events, S_S only for subduction slab events and S_k for each of the site classes ($k = 1, \ldots, 4$). $\delta_h = 0$ for $h < h_c$ and 1 otherwise. For $h > 125\,\mathrm{km}$ use $h = 125\,\mathrm{km}$.

- Use four site categories:

  SC I Rock, natural period $T < 0.2\,\mathrm{s}$, $V_{s,30} > 600\,\mathrm{m/s}$, approximately NEHRP classes A and B. 1381 records.

  SC II Hard soil, natural period $0.2 \leq T < 0.4\,\mathrm{s}$, $300 < V_{s,30} \leq 600\,\mathrm{m/s}$, approximately NEHRP class C. 1425 records.

  SC III Medium soil, natural period $0.4 \leq T < 0.6\,\mathrm{s}$, $200 < V_{s,30} \leq 300\,\mathrm{m/s}$, approximately NEHRP class D. 594 records.

  SC IV Soft soil, natural period $T \geq 0.6\,\mathrm{s}$, $V_{s,30} \leq 200\,\mathrm{m/s}$, approximately NEHRP classes E and F. 938 records.

  Site classification unknown for 62 records. Prefer using site classes rather than individual coefficients for each station because avoids possibility of source effects being shifted into site terms and can be used when there are only a few records per station.

- Response parameter is acceleration for 5% damping.

- Classify earthquakes into three types:

  Crustal Focal depths $\leq 25\,\mathrm{km}$. 81 earthquakes, 1497 records.

  Interface 88 earthquakes, 1188 records.

  Slab 101 earthquakes. 1715 records.

- Classify earthquakes into four mechanisms:

  Reverse 160 earthquakes (28 crustal), 1969 records (373 crustal).

  Strike-slip 82 earthquakes (39 crustal), 1674 records (1100 crustal).

  Normal 26 earthquakes (4 crustal), 749 records (24 crustal).

  Unknown 2 earthquakes (0 crustal), 8 records (0 crustal).

  Consider differences between reverse and strike-slip motions for crustal earthquakes because enough data but note there is not enough data to consider normal earthquakes as a separate group.

- Focal depths, h, between about 0 and $162\,\mathrm{km}$ with most $< 60\,\mathrm{km}$.

- Exclude data from distances greater than a specified limit for a given magnitude in order to eliminate bias due to untriggered instruments. For subduction slab events, fix maximum distance as $300\,\mathrm{km}$.

- Note that there is little near-source data from Japan from within $30\,\mathrm{km}$. All Japanese data from within $10\,\mathrm{km}$ is from two earthquakes (Kobe 1995 and Tottori 2000). Add data from with $40\,\mathrm{km}$ from earthquakes in western USA ($h < 20\,\mathrm{km}$) and from the Tabas 1978 (Iran) earthquake to help constrain near-source behaviour of derived equations. Use data from: Japan (61 crustal earthquakes, 1301 records; 87 interface earthquakes, 1176 records; 101 slab earthquakes, 1715 records) and Iran and western USA (20 crustal earthquakes; 196 records; 1 interface earthquake, 12 records).
- Note that reasonably good distribution of data for all magnitudes and focal depths.
- Note strong correlation between focal depth and distance.
- Use ISC relocations rather than JMA locations because find that they are more reliable.
- Use M_w values from Harvard CMT unless value from special study is available.
- Prefer the one-stage maximum-likelihood method to the two-stage method because when there many events with only a small number of records and many individual site terms, the coefficients must be determined using an iterative method and hence their reliability is questionable.
- Find that, by residual analysis (not shown), that equations predict unbiased ground motions for crustal and interface events but biased ground motions for slab events with bias that depends on distance. Apply this magnitude-independent path modification factor SF for slab events: $\log(\mathrm{SF}) = S_{\mathrm{SL}}[\log(\sqrt{x^2 + R_a^2}) - \log(R_c)]$ where $R_a = 90.0\,\mathrm{km}$ and $R_c = 125.0\,\mathrm{km}$.
- Find that, because of lack of near-source data, it is not possible to find reliable estimates of c and d so use a iterative method to find d by fixing c.
- Estimate site coefficient, S_H, for hard rock sites ($V_{s,30} = 1500\,\mathrm{m/s}$) from 10 stations with $1020 \leq V_{s,30} \leq 2200\,\mathrm{m/s}$ with 1436 records, based on residuals.
- Examine residuals w.r.t. magnitude, distance and focal depth for all three source types and find no significant bias. Find that PGAs from two events on east coast of Hokkaido are under-estimated and note that investigation needed to see if it is a regional anomaly. Also find that ground motions from 2003 Miyagi ($M_w 7.0$) event are under-estimated, which note is due to a known regional anomaly.
- Believe model more robust than other models for subduction events due to lower prediction errors.
- Note that predictions for near-source ground motion for subduction events are largely constrained by data from shallow crustal events from western USA hence adding subduction records from $< 50\,\mathrm{km}$ could result in improvements.

4.120 Yu & Hu (2004)

- Ground-motion model is:

$$\log Y = c_1 + c_2 M + c_3 \log(R + c_4 \mathrm{e}^{c_5 M})$$

- Response parameter is acceleration for 5% damping.

- Use data from 377 sites with $V_{s,30} > 500\,\mathrm{m/s}$.
- Use data from the Trinet broadband high and low gain channels (BH and HL). BH are STS-1 and STS-2 instruments and HL are mainly FBA-23 instruments. Use BH data when not clipped and otherwise HL data.
- Eliminate DC offset for each record. Convert ground motions into acceleration while applying a high-pass filter with cut-off of $40\,\mathrm{s}$. Display recovered acceleration, velocity and displacement time-histories from a $M_L 5.1$ earthquake from the BH and HL data. Note that they are similar and hence that reliable ground motion can be recovered from these data.
- Display the signal and noise Fourier amplitude spectra for one record and find that the signal-to-noise ratio is higher in the BH channel than in the HL channel. State that the signal-to-noise ratio is still > 1 for periods of $20\,\mathrm{s}$ for both types of data.
- Compute acceleration and relative displacement response spectra for both channels. Find that for periods $> 0.3\,\mathrm{s}$ the response spectra from the two channels are very close. State that the difference for short periods is due to the low sampling rate ($20\,\mathrm{sps}$) for the BH channel and the higher (80 or $100\,\mathrm{sps}$) sampling rate for HL channel.
- Conclude that reliable ground motions up to $20\,\mathrm{s}$ can be recovered from these data.
- Use a two-stage regression method where first determine c_4 and c_5 and then the other coefficients.
- Most data from digital instruments from $M \leq 5.5$ and $R < 300\,\mathrm{km}$. Most data from analogue instruments from $6.0 \leq M \leq 7.0$ and $10 < R < 100\,\mathrm{km}$.
- Use data from analogue instruments for short-period range (0.04–$3\,\mathrm{s}$) and data from Trinet instruments for long-period range (1–$20\,\mathrm{s}$). Connect the two sets of coefficients at $1.5\,\mathrm{s}$ after confirming that the predictions match at this period.
- Do not give coefficients only predictions.

4.121 Ambraseys *et al.* (2005a)

- See Section 2.207.
- Response parameter is acceleration for 5% damping.
- Only use spectral accelerations within passband of filter ($1.25 f_l$ and f_h) where f_l is the low cut-off frequency and f_h is the high roll-off frequency.
- Note that after $0.8\,\mathrm{s}$ the number of records available for regression analysis starts to decrease rapidly and that after $4\,\mathrm{s}$ there are few records available. Only conduct regression analysis up to $2.5\,\mathrm{s}$ because for longer periods there are too few records to obtain stable results. Note that larger amplitude ground motions are better represented in the set for long-periods ($> 1\,\mathrm{s}$).
- Find that logarithmic transformation may not be justified for nine periods (0.26, 0.28 and 0.44–$0.65\,\mathrm{s}$) by using pure error analysis but use logarithmic transformation since it is justified for neighbouring periods.

- By using pure error analysis, find that for periods $> 0.95\,\mathrm{s}$ the null hypothesis of a magnitude-independent standard deviation cannot be rejected so assume magnitude-independent σ. Note that could be because magnitude-dependent standard deviations are a short-period characteristic of ground motions or because the distribution of data w.r.t. magnitude changes at long periods due to filtering.
- Find that different coefficients are significant at different periods so try changing the functional form to exclude insignificant coefficients and then applying regression again. Find that predicted spectra show considerable variation between neighbouring periods therefore retained all coefficients for all periods even when not significant.
- Note that smoothing could improve the reliability of long-period ground-motion estimates because they were based on less data but that smoothing is not undertaken since the change of weighted to unweighted regression at $0.95\,\mathrm{s}$ means a simple function cannot fit both short- and long-period coefficients.

4.122 Ambraseys *et al.* (2005b)

- See Section 2.208.
- Response parameter is acceleration for 5% damping.
- By using pure error analysis, find that for periods 0.15–0.40, 0.60–0.65, 0.75 and $0.85\,\mathrm{s}$ the null hypothesis of a magnitude-independent standard deviation be rejected so use weighted regression for these periods.

4.123 Bragato & Slejko (2005)

- See Section 2.210.
- Response parameter is acceleration for 5% damping.

4.124 García *et al.* (2005)

- See Section 2.212.
- Response parameter is pseudo-acceleration for 5% damping.
- No coefficient smoothing performed because coefficients w.r.t. frequency show acceptable behaviour.

4.125 McGarr & Fletcher (2005)

- See Section 2.214.
- Response parameter is pseudo-velocity for 5% damping.
- Constrain k to 0 for $T \geq 0.5\,\mathrm{s}$ because otherwise positive.

4.126 Pousse *et al.* (2005)

- Ground-motion model is:

$$\log_{10}(\mathrm{PSA}(f)) = a(f)M + b(f)X - \log_{10}(X) + S_k$$

  Select this form to compare results with Berge-Thierry *et al.* (2003).

- Use five Eurocode 8 categories:

  A $V_{s,30} > 800\,\mathrm{m/s}$, use S_1

  B $360 < V_{s,30} < 800\,\mathrm{m/s}$, use S_2

  C $180 < V_{s,30} < 360\,\mathrm{m/s}$, use S_3

  D $V_{s,30} < 180\,\mathrm{m/s}$, use S_4

  E Soil D or C underlain in first $20\,\mathrm{m}$ by a layer of $V_{s,30} > 800\,\mathrm{m/s}$, use S_5

  where $V_{s,30}$ is average shear-wave velocity in upper $30\,\mathrm{m}$. Since soil profiles only available up to $20\,\mathrm{m}$, use method of Atkinson & Boore (2003) to assign sites to categories using Kik-Net profiles to define probability curves. Generate five redistributions to test stability of results. Find coefficients and σ relative stable (changes less than 10%) except for site class A (changes up to 50%.

- Response parameter is pseudo-acceleration for 5% damping.

- Use data from the K-Net and Kik-Net networks.

- Process records using non-causal 4 pole Butterworth filter with cut-offs of 0.25 and $25\,\mathrm{Hz}$ for consistency with earlier studies.

- Select records from events with $M_w > 4$ and with focal depth $< 25\,\mathrm{km}$ to exclude records of subduction events and to remain close to tectonic conditions in France.

- Exclude records from distances greater than a the distance predicted by a magnitude-dependent equation predicting the location of a PGA threshold of $10\,\mathrm{cm/s}^2$ (corresponding to trigger of older Japanese sensors) to prevent possible underestimation of attenuation rate.

- Visually inspect records to check for glitches and to use only main shock if multiple events present.

- Convert M_{JMA} to M_w to compare results with other studies.

- For 10 large earthquakes for which source dimensions are known use r_{rup}.

- Note good distribution w.r.t. M_w and r_{rup} except between 6.1 and 7.3 where only two events.

- Find that pseudo-acceleration at $0.01\,\mathrm{s}$ equals PGA.

- Also compute coefficients using geometric mean and find identical coefficients and standard deviations lower by 0.02.

- Find σ lower when use five site classes than when no site information is used.

- Find peak in σ at about $1\,\mathrm{s}$. Peak also present when unfiltered data used. Also present when data from different magnitude ranges (4.0–4.5, 4.0–5.0, 4.0–5.5 and 4.0–6.0) are used.
- Note that results for site class E are uncertain due to limited number of records.
- Examine residuals w.r.t. distance and magnitude and find no significant bias.
- Examine quartile plots of residuals and find that residuals are normally distributed up to 2–4 σs. All pass Kolmogorov-Smirnov test at 5% significance level for normality except at $0.01\,\mathrm{s}$.
- Conducted sensitivity analysis by changing minimum magnitude, geographical area and minimum number of events recorded at each station. Find dependence of σ on period was similar as were site coefficients. b shows some variations.
- Coefficients not reported.

4.127 Takahashi *et al.* (2005), Zhao *et al.* (2006) and Fukushima *et al.* (2006)

- See Section 2.217.
- Response parameter is acceleration for 5% damping.

4.128 Wald *et al.* (2005)

- See Section 2.218.
- Response parameter is pseudo-acceleration for 5% damping.

4.129 Atkinson (2006)

- See Section 2.219.
- Response parameter is pseudo-acceleration for 5% damping.
- Compares predictions to observations grouped into 1-unit magnitude bins at 0.3 and $1.0\,\mathrm{s}$ and finds equations are reasonable description of data. Also compares predictions to observations from large magnitudes events and from close distances and finds that equations would overestimate short-period motions from large events at close distances.
- Compares overall distribution of residuals for $0.3\,\mathrm{s}$ with normal distribution. Finds that residuals generally follow normal distribution but data shows greater number of large-residual observations that predicted by normal distribution, most of which come from a single event (22/02/2000 $\mathbf{M}3.24$) recorded at $> 100\,\mathrm{km}$. Finds no evidence for truncation of residuals up to three standard deviations.

- For analysis of Landers events, regresses $0.3\,\mathrm{s}$ data for 10 stations with more than 50 records using same functional form without distance terms (since distances are almost constant) to get site-specific equations. Find on average $\sigma = 0.19 \pm 0.04$. Therefore concludes single station-single source standard deviations much lower (60%) than standard σs.
- Notes that decreasing σ with increasing period could be due to dominance of small events for which long-period motions are at the moment end of the spectrum, which should be correlated with $\mathbf{M}$ and independent of stress drop.

4.130 Beyer & Bommer (2006)

- See Section 2.220.
- Response parameter is acceleration for 5% damping.
- Use records only up to maximum usable period specified in NGA database.

4.131 Bindi *et al.* (2006)

- See Section 2.221.
- Response parameter is pseudo-velocity for 5% damping.
- Only use records from within passband of filter. For $T > 2\,\mathrm{s}$ only use digital records.

4.132 Campbell & Bozorgnia (2006a) and Campbell & Bozorgnia (2006b)

- See Section 2.222.
- Response parameter is pseudo-acceleration for 5% damping.

4.133 Hernandez *et al.* (2006)

- See Section 2.225.
- Response parameter is pseudo-acceleration for 5% damping.

4.134 Kanno *et al.* (2006)

- See Section 2.226.
- Response parameter is acceleration for 5% damping.
- Note the poorer correlation between residuals and $V_{s,30}$ for short periods could be due to higher modal effects or to nonlinear effects (although note that few records where nonlinear effects are likely).

4.135 McVerry *et al.* (2006)

- See Section 2.230.
- Response parameter is acceleration for 5% damping.

4.136 Pousse *et al.* (2006)

- See Section 2.232.
- Response parameter is pseudo-acceleration for 5% damping.
- Coefficients not reported.

4.137 Sakamoto *et al.* (2006)

- Ground-motion model is:

$$\begin{aligned}\log \mathrm{SA}(T) &= a(T)M_w + b(T)X + g + d(T)D + c(T) \\ \text{where}\quad g &= -\log(X+e) \quad \text{for} \quad D \leq 30\,\mathrm{km} \\ g &= 0.4\log(1.7D+e) - 1.4\log(X+e) \quad \text{for} \quad D > 30\,\mathrm{km} \\ e &= 0.00610^{0.5M_w}\end{aligned}$$

- Soil characteristics known to bedrock for 571 (out of 1013) stations. Classify stations using NEHRP classification using $V_{s,30}$ or converted N-values:

  A $V_{s,30} > 1500\,\mathrm{m/s}$, 0 stations

  B $760 < V_{s,30} \leq 1500\,\mathrm{m/s}$, 0 stations

  C1 $460 < V_{s,30} \leq 760\,\mathrm{m/s}$, 174 stations

  C2 $360 < V_{s,30} \leq 460\,\mathrm{m/s}$, 193 stations

  D1 $250 < V_{s,30} \leq 360\,\mathrm{m/s}$, 300 stations

  D2 $180 < V_{s,30} \leq 250\,\mathrm{m/s}$, 230 stations

  E $V_{s,30} \leq 180\,\mathrm{m/s}$, 116 stations

  Define nonlinear (based on PGA at bedrock) soil amplification model using nonlinear analyses of sampled soil conditions for each class of soils. Use this model to convert observed ground motion to motion at a C1 site.

- Response parameter is acceleration for 5% damping.
- Focal depths, D, between 3 and $122\,\mathrm{km}$.
- Distribution with respective to earthquake type (based on mechanism, location and depth) is: crustal ($3 \leq D \lesssim 25\,\mathrm{km}$), 13; interplate ($10 \lesssim D \lesssim 70\,\mathrm{km}$), 23; and intraplate, 16 ($30 \lesssim D \leq 122\,\mathrm{km}$).
- PGA from 2 to $1114\,\mathrm{cm/s^2}$.

- Try including different constant terms to model effect of earthquake type but find lower statistical confidences of results. Therefore remove these coefficients. Believe that modelling of focal-depth dependency may already include effect of earthquake type due to high correlation between depth and type.
- Fit fourth-degree polynomials (in $\log(T)$) through derived coefficients to generate smooth spectra.
- Compare inter- and intra-event residuals to normal distribution using Kolmogorov-Smirnov test and find that the intra-event residuals have a normal distribution and that the inter-event residuals almost have.
- Examine magnitude-dependence of the standard deviations using residuals binned within different magnitude ranges ($M_w < 6.0$, $6.0 \leq M_w < 6.5$, $6.5 \leq M_w < 7.0$ and $M_w \geq 7.0$) and do not find a clear trend for either inter- or intra-event residuals.
- Examine distance-dependence of the intra-event standard deviations and find that for some periods the standard deviations show some depth-dependence for short and long distances.
- Examine amplitude-dependence of the intra-event standard deviations and find some positive dependence (σ increases for higher amplitude motions) for $T \leq 0.4\,\mathrm{s}$. Note that this may be due to a lack of small amplitude motions due to nontriggering of instruments.

4.138 Sharma & Bungum (2006)

- Ground-motion model is:

$$\ln(A) = c_2 M - b \ln(X + \exp(c_3 M))$$

- Response parameter is acceleration for an unspecified damping (but assumed to be 5%).
- Use two site classes:

  R Rock. Generally granite/quartzite/sandstone.

  S Soil. Sites with exposed soil cover with different levels of consolidation.

- Data from three strong-motion (SMA-1) arrays: Kangra, Uttar Pradesh and Shillong, in the Himalayas.
- Instruments generally from ground floors of buildings.
- Rotate components into NS and EW directions.
- Focal depths between 7 and $121\,\mathrm{km}$.
- Note that distribution of records is uneven. Five events have less than 9 records and one earthquake has 43.
- Note that M_w avoids magnitude saturation problems.

- Note that lack of near-field data (all but one record from $> 20\,\mathrm{km}$) means that results are not stable. Therefore introduce nine European records from seven reverse-faulting earthquakes for $M \geq 6.0$ and $d_e \leq 20\,\mathrm{km}$.
- Use method of Campbell (1981) to avoid problems due to correlation between magnitude and distance. Divide data into a number of subsets based on distance. For each interval, each earthquake is given equal weight by assigning a relative weight of $1/n_{j,l}$ to the record where $n_{j,l}$ is the total number of records from the jth earthquake within ith distance bin. Normalise weights so that they sum to total number of records. Use distance bins of $5\,\mathrm{km}$ wide up to $10\,\mathrm{km}$ and then bins of equal width w.r.t. logarithmic distance.
- Use r_{hypo} rather than r_{rup} because: a) large depth of some events and b) poorly known fault geometries. Note that r_{hypo} has a reasonable seismological basis and can be reliably and easily determined for most significant (including hypothetical design) earthquakes.
- Regress all data using: $\ln(A) = c - b\ln(X)$ and find $b = 1.22 \pm 0.69$. Next regress using: $\ln(A) = aM - b\ln(X) + c$ and find $b = 0.515 \pm 0.081$. Conclude that this is due to correlation between magnitude and distance and hence conduct the first step of a two-step regression with dummy variables for each earthquake. Find a decay rate of -1.20 ± 0.036. Use this fixed decay rate for rest of analysis.
- Try to regress on rock and soil data simultaneously by including a linear site term $c_4 S_{SR}$ but find that there are problems during the regression process. Hence regress separately on rock and soil data.

4.139 Zare & Sabzali (2006)

- See Section 2.234.
- Response parameter is not given but assumed to be acceleration for 5% damping.

4.140 Akkar & Bommer (2007b)

- See Section 2.235.
- Response parameter is displacement for 2, 5, 10, 20 and 30% damping. Choose displacement because of aimed use of equations for displacement-based design.
- Only use records within their usable range, defined as a fraction of the cut-off frequency used and depending on instrument type (digital or analogue), magnitude and site class.
- Note that drop-off in available records from analogue instruments is much more rapid (starting around $1\,\mathrm{s}$) than for records from digital instruments (starting around $3\,\mathrm{s}$). Due to lack of data for longer periods limit regression to periods $\leq 4\,\mathrm{s}$.
- Due to jagged appearance of predicted response spectra, particularly at long periods where different data was used for each period, apply negative exponential smoothing. Try smoothing using low-order polynomials, to achieve very smooth spectra, but complex functional form means results are sensitive to trade-offs between smoothed coefficients.

Find that for periods $> 3\,\mathrm{s}$ spectra predicted from the raw and smoothed coefficients show differences, especially for low damping ratios.

- Find that coefficients b_7-b_{10} weakly dependent on damping ratio so present these coefficients for 2 and 5% damping (combined), 10% and 20 and 30% damping (combined).

4.141 Bindi *et al.* (2007)

- See Section 2.238.
- Response parameter is acceleration for 5% damping.
- Display graphs of inter-, intra-event and total standard deviations against period when using M_w or M_L.

4.142 Bommer *et al.* (2007)

- See Section 2.239.
- Response parameter is pseudo-acceleration for 5% damping.
- Derive equations only up to $0.5\,\mathrm{s}$ because thought that ground motions reliable up to this limit and since equations developed only for comparative purposes. Note that usable period range of data could be extended to $2\,\mathrm{s}$ but since study is for exploring influence of lower magnitude limit short-period motions are the most important.

4.143 Boore & Atkinson (2007) & Boore & Atkinson (2008)

- See Section 2.240.
- Response parameter is pseudo-acceleration for 5% damping.
- Do not use pseudo-accelerations at periods $> T_{MAX}$, the inverse of the lowest useable frequency in the NGA Flatfile.
- Constant number of records to $1\,\mathrm{s}$, slight decrease at $2\,\mathrm{s}$ and a rapid fall off in number of records for periods $> 2\,\mathrm{s}$.
- For long periods very few records for small earthquakes ($M < 6.5$) at any distance so magnitude scaling at long periods poorly determined for small events.
- Choi & Stewart (2005) do not provide coefficients for site amplification for periods $> 5\,\mathrm{s}$ so linearly extrapolate b_{lin} in terms of log period by assuming relative linear site amplification to decrease.
- To assign c_3 for entire period range fit quadratic to c_3s from four-event analysis with constraints for short and long periods.
- No data from normal-faulting events for $10\,\mathrm{s}$ so assume ratio of motions for normal and unspecified faults is same as for $7.5\,\mathrm{s}$.
- Possible underprediction of long-period motions at large distances in deep basins.

- Chi-Chi data major controlling factor for predictions for periods $> 5\,\mathrm{s}$ even for small events.

4.144 Campbell & Bozorgnia (2007), Campbell & Bozorgnia (2008b) & Campbell & Bozorgnia (2008a)

- See Section 2.241.
- Response parameter is pseudo-acceleration (PSA) for 5% damping.
- If PSA $<$ PGA for $T \leq 0.25\,\mathrm{s}$ then set PSA equal to PGA, to be consistent with definition of PSA (occurs for large distances and small magnitudes).
- Due to cut-off frequencies used number of records available for periods > 4–$5\,\mathrm{s}$ falls off significantly. Majority of earthquakes at long periods are for $6.5 \leq M \leq 7.9$ and 70% are from 1999 Chi-Chi earthquake.
- To extend model to longer periods and small magnitudes constrain the magnitude-scaling term using empirical observations and simple seismological theory.

4.145 Danciu & Tselentis (2007a) & Danciu & Tselentis (2007b)

- See Section 2.242.
- Response parameter is acceleration for 5% damping.

4.146 Fukushima *et al.* (2007b) & Fukushima *et al.* (2007a)

- Ground-motion model is [same as Fukushima *et al.* (2003)]:

$$\log_{10}(\mathrm{Sa}(f)) = a(f)M - \log_{10}(R + d(f) \times 10^{e(f)M}) + b(f)R + \Sigma c_j(f)\delta_j$$

  $\delta_j = 1$ for jth site class and 0 otherwise.

- Use five site categories:

  SC-1 Site natural period $T_G < 0.2\,\mathrm{s}$, $V_{s,30} > 600\,\mathrm{m/s}$, NEHRP classes A+B. 23 sites.

  SC-2 Site natural period $0.2 \leq T_G < 0.6\,\mathrm{s}$, $200 \leq V_{s,30} < 600\,\mathrm{m/s}$, NEHRP classes C+D. 100 sites.

  SC-3 Site natural period $T_G \geq 0.6\,\mathrm{s}$, $V_{s,30} \leq 200\,\mathrm{m/s}$, NEHRP class E. 95 sites.

  SC-4 Unknown site natural period, $V_{s,30} > 800\,\mathrm{m/s}$, NEHRP classes A+B. 44 sites.

  SC-5 Unknown site natural period, $300 \leq V_{s,30} < 800\,\mathrm{m/s}$, NEHRP class C. 79 sites.

  Manually classify stations using the predominant period computed using average horizontal-to-vertical (H/V) response spectral ratios using similar approach to Zhao *et al.* (2006) and also mean residuals w.r.t. equations of Fukushima *et al.* (2003). Reclassify stations of Fukushima *et al.* (2003), who used rock/soil classes. Some (36%) stations cannot be classified (due to, e.g., broadband amplification) using this approach so retain rock/soil classes for these records. Use this approach since limited geotechnical data is available for most sites in their dataset. Only roughly 30% of stations have multiple records so the average H/V ratios are not statistically robust so do not use automatic classification approach. Each co-author independently classified stations. About 90% of classifications agreed. After discussion the stations were reclassified. Originally used same categories as Zhao *et al.* (2006) but find their class SC-III too narrow so combine it with their SC-II to form SC-2. Find similar average ratios for the different categories as Zhao *et al.* (2006).

- Response parameter is acceleration for 5% damping.
- Use data and regression method of Fukushima *et al.* (2003). Eliminate data from two stations of Fukushima *et al.* (2003) because of suspected soil-structure interaction.
- Coefficients not reported since focus of article is the site classification procedure and its impact on predicted response spectra and not to propose a new model for seismic hazard assessment.
- Records filtered with cut-offs at 0.25 and $25\,\mathrm{Hz}$ therefore present results up to $3\,\mathrm{s}$ to avoid filter effects.
- Find roughly 2% reduction in standard deviation using classification scheme compared to rock/soil scheme.

4.147 Hong & Goda (2007) & Goda & Hong (2008)

- See Section 2.244.
- Response parameter is pseudo-acceleration for 5% damping.
- Select the period range of usable PSA values based on cut-off frequencies of the high-pass filters used to correct records.
- Develop an orientation-dependent ground-motion measure based on maximum resultant response and ratio between response of an (arbitrarily) oriented SDOF system and maximum resultant response.
- Derive equations for the probability of exceedance for SDOF systems designed for different ways of combining the two horizontal components subjected to ground motions from an unknown direction.
- Investigate record-to-record variability of response and implied exceedance probability using a set of 108 records used by Boore *et al.* (1997) for 0.2 and $1.0\,\mathrm{s}$. Conclude that when using common methods for combining two horizontal components (such as geometric mean) that meaning of the return period of uniform hazard spectra is not clear because the major and minor axes of shaking are unknown before an event.
- Investigate SA resolved for different directions normalized by SA along the major axis for all selected records. Conclude that knowing SA along the major axis and the normalized SA for different direction completely defines the response in any direction. Derive empirical equation for the normalized SA w.r.t. angle and its probability distribution.
- Only report coefficients for 0.2, 0.3, 1, 2 and $3\,\mathrm{s}$ in article. Provide coefficients for other periods as electronic supplement.

4.148 Massa *et al.* (2007)

- See Section 2.246.
- Response parameter is acceleration for 5% damping.

4.149 Tejeda-Jácome & Chávez-García (2007)

- See Section 2.250.
- Response parameter is pseudo-acceleration for 5% damping.
- Signal-to-noise ratios mean analysis limited to $1\,\mathrm{s}$ for horizontal and $0.8\,\mathrm{s}$ for vertical.

4.150 Abrahamson & Silva (2008) & Abrahamson & Silva (2009)

- See Section 2.251.
- Response parameter is pseudo-acceleration for 5% damping.
- Records only used for spectral frequencies 1.25 times the high-pass corner frequency used in the record processing. Therefore, number of records and earthquakes available for regression decreases with increasing period.
- Fix a_2, a_{12}, a_{13}, a_{16} and a_{18} at their values for 2–$4\,\mathrm{s}$ for $T > 5\,\mathrm{s}$ because they could not be constrained by data.
- Smooth coefficients in several steps.

4.151 Aghabarati & Tehranizadeh (2008)

- See Section 2.253.
- Response parameter is pseudo-acceleration for 5% damping.

4.152 Cauzzi & Faccioli (2008), Cauzzi (2008) & Cauzzi *et al.* (2008)

- See Section 2.254.
- Response parameter is displacement for 5, 10, 20 and 30% damping.
- Coefficients reported as Electronic Supplementary Material.
- Try replacing site terms: a_B, a_C and a_D by $b_4 10^{b_5 M_w}$, $b_6 10^{b_7 M_w}$ and $b_8 10^{b_9 M_w}$ but do not report coefficients since did not lead to reduction in standard deviation.
- Compare predictions and observations for Parkfield 2004 earthquake. Find good match.
- Study residuals for site classes B, C and D w.r.t. predicted ground motion to check for nonlinear site response. Find some evidence for moderate nonlinear effects in limited period ranges.

4.153 Chen & Yu (2008b)

- Ground-motion model is:

$$\log \mathrm{Sa} = C_1 + C_2 M + C_3 M^2 + C_4 \log[R + C_5 \exp(C_6 M)]$$

- Use records from sites with $V_{s,30} \geq 500\,\mathrm{m/s}$.
- Use the NGA Flatfile.
- Response parameter is acceleration for 5% damping.
- Data divided into magnitude intervals of: 5.0–5.4, 5.5–5.9, 6.0–6.4, 6.5–6.9 and 7.0–7.5 and distance intervals of: 0–$2.9\,\mathrm{km}$, 3.0–$9.9\,\mathrm{km}$, 10–$29.9\,\mathrm{km}$, $30-59.9\,\mathrm{km}$, $60\text{-}99.9\,\mathrm{km}$, 100–$200\,\mathrm{km}$ and $> 200\,\mathrm{km}$. Use weighted regression with weights given by inverse of number of records in each magnitude-distance bin since most data from moderate earthquakes at intermediate distances.
- Compute C_5 and C_6 using data from six earthquakes: 1979 Imperial Valley ($M6.53$), 1980 Livermore ($M5.42$), 1989 Loma Prieta ($M6.93$), 1992 Landers ($M7.28$), 1999 Hector Mine ($M7.13$) and 2004 Parkfield ($M5.9$).

4.154 Chen & Yu (2008a)

- Response parameter is acceleration for 0.5, 2, 7, 10 and 20% damping.
- Continuation of Chen & Yu (2008b) (Section 4.153) for other damping levels.

4.155 Chiou & Youngs (2008)

- See Section 2.255.
- Response parameter is pseudo-acceleration for 5% damping.
- Coefficients developed through iterative process of performing regressions for entire spectral period range with some parts of model fixed, developing smoothing models for these coefficients with period, and then repeating analysis to examine variation of remaining coefficients. Note noticeable steps in c_1 at 0.8, 1.1, 1.6, 4.0 and $8.0\,\mathrm{s}$, where there is large reduction in usable data. Suggest that this could indicate bias due to systematic removal of weaker motions from data set. To correct this bias and to smooth c_1 impose smooth variation in slope of c_1 w.r.t. period. Also examine shape of displacement spectra for $M \geq 6.5$ to verify that constant displacement reached at periods expected by design spectra.

4.156 Cotton *et al.* (2008)

- See Section 2.256.
- Response parameter is pseudo-acceleration for 5% damping.

4.157 Dhakal *et al.* (2008)

- Ground-motion model is:

$$\log_{10} Y(T) = c + aM_w + hD - \log_{10} R - b_1 R_1 - b_2 R_2$$

- Response parameter is pseudo-velocity for 5% damping.
- Use R_1, distance from hypocentre to volcanic front, and R_2, distance from volcanic front to site, to model anelastic attenuation.
- Use data from K-Net. Select earthquakes that: 1) have $M_w > 5$ and 2) have more than 50 available records. To remove bias due to large number of records from fore-arc site compared to back-arc, select only those earthquakes with 40% of the available records within $300\,\mathrm{km}$ are from back-arc region. Use both interplate and intraslab events occurring in fore-arc region so that effect of low Q zone is clearly seen. Only use records up to $300\,\mathrm{km}$ so that peaks are due to S-wave motions. Exclude records from $M_w 8$ earthquakes because these events radiate strong surface waves so assumption of S-wave peaks may not be valid.
- Focal depths, D, of intraslab earthquakes between 59 and $126\,\mathrm{km}$ and for interface[10] earthquakes between 21 and $51\,\mathrm{km}$.
- Also derive model using: $\log_{10} Y(T) = c + aM_w + hD - \log_{10} R - bR$. Find lower σs for functional form using R_1 and R_2 for periods $< 1\,\mathrm{s}$. Examine residuals w.r.t. r_{hypo} for 0.1 and $1.0\,\mathrm{s}$ with grey scale indicating ratio $R_1/(R_1 + R_2)$ for this functional form. Note that fore-arc sites have positive residuals and back-arc sites negative residuals. Also plot residuals for selected functional form and find that residuals do not show difference between fore-arc and back-arc sites.
- Regress separately for intraslab and interface earthquakes because source characteristics significantly different.
- Find that the coefficients for anelastic attenuation for fore-arc and back-arc different for periods $< 2\,\mathrm{s}$.
- Convert computed anelastic coefficients to Q models and find that can relate observations to different Q models for fore-arc and back-arc regions.

4.158 Idriss (2008)

- See Section 2.258.
- Response parameter is pseudo-acceleration for 5% damping.
- Uses all records (including those from Chi-Chi) to constrain coefficients for $1.5 \leq T \leq 5\,\mathrm{s}$ because influence of Chi-Chi records decreases with increasing period.
- Uses smoothed plots to obtain coefficients for $T > 5\,\mathrm{s}$ because of lack of records.

[10]Authors call them 'interplate'.

4.159 Lin & Lee (2008)

- See Section 2.259.
- Response parameter is acceleration for 5% damping.

4.160 Massa *et al.* (2008)

- See Section 2.260.
- Response parameters are acceleration and pseudo-velocity for 5% damping.

4.161 Morasca *et al.* (2008)

- See Section 2.262.
- Response parameter is pseudo-velocity for 5% damping.

4.162 Yuzawa & Kudo (2008)

- Ground-motion model is:

$$\log S(T) = a(T)M - [\log X_{eq} + b(T)X_{eq}] + c(T)$$

- Response parameter is acceleration for 5% damping.
- Use data from KiK-Net at hard rock sites with shear-wave velocity $V_s \geq 2.0\,\mathrm{km/s}$ at surface and/or in borehole. Select records from 161 sites (out of 670 sites of KiK-Net) where spectral ratio between surface and borehole records ≤ 2 at periods $> 1\,\mathrm{s}$. Note that preferable to use higher velocity $(3.0\,\mathrm{km/s})$ but as velocity increases number of available sites rapidly decreases: 43 sites with $V_s = 2.0$–$2.2\,\mathrm{km/s}$, 33 with $V_s = 2.2$–2.4, 27 with $V_s = 2.4$–2.6, 31 with $V_s = 2.6$–2.8, 16 with $V_s = 2.8$–3.0, 8 with $V_s = 3.0$–3.2 and 3 with $V_s > 3.2\,\mathrm{km/s}$.
- Select earthquakes based on their magnitudes, horizontal locations and depths and types (crustal, interface and intraslab). Note that geographical distribution is not homogeneous but it covers whole of Japan.
- Focal depths between 8.58 and $222.25\,\mathrm{km}$.
- Also derive model using M_w. Find predictions similar so use prefer M_{JMA} for convenience of application in Japan.
- Only graphs of coefficients presented.

4.163 Aghabarati & Tehranizadeh (2009)

- See Section 2.265.
- Response parameter is pseudo-acceleration for 5% damping.

4.164 Akyol & Karagöz (2009)

- See Section 2.266.
- Response parameter is acceleration for 5% damping.
- Observe nonlinear site effects in residuals for periods $\leq 0.27\,\mathrm{s}$, which model using site coefficient correction terms.

4.165 Bindi *et al.* (2009a)

- See Section 2.267.
- Response parameter is acceleration for 5% damping.

4.166 Bindi *et al.* (2009b)

- See Section 2.268.
- Response parameter is acceleration for 5% damping.

4.167 Bragato (2009)

- See Section 2.269.
- Response parameter is acceleration for 5% damping.
- Coefficients not reported, only σs.

4.168 Ghasemi *et al.* (2009)

- Ground-motion model is:

$$\log_{10} \mathrm{Sa} = a_1 + a_2 M + a_3 \log_{10}(R + a_4 10^{a_5 M}) + a_6 S_1 + a_7 S_2$$

  after trying various other functional forms. Fix a_5 to 0.42 from previous study due to lack of near-field data and unstable regression results.

- Use two site classes:

  Rock $V_{s,30} \geq 760\,\mathrm{m/s}$. $S_1 = 1$, $S_2 = 0$.

  Soil $V_{s,30} < 760\,\mathrm{m/s}$. $S_2 = 1$, $S_1 = 0$.

  Classify station using $V_{s,30}$ and surface geology data, if available. Otherwise use empirical H/V classification scheme.

- Response parameter is acceleration for 5% damping.

- Investigate differences in ground motions between Alborz-Central Iran and Zagros regions using analysis of variance (ANOVA) (Douglas, 2004b) to check whether data can be combined into one dataset. Find that for only one magnitude-distance interval out of 30 is there a significant difference in ground motions between the two regions. Hence, combine two datasets.
- Check that data from West Eurasia and Kobe from Fukushima *et al.* (2003) can be combined with data from Iran using ANOVA. Find that for only one magnitude-distance interval is there a significant difference in ground motions and, therefore, the datasets are combined.
- Only retain data from $R < 100\,\mathrm{km}$ to avoid bias due to non-triggered instruments and because data from greater distances is of low engineering significance.
- Process uncorrected records by fitting quadratic to velocity data and then filtering acceleration using a fourth-order acausal Butterworth filter after zero padding. Choose filter cut-offs by using the signal-to-noise ratio using the pre-event noise for digital records and the shape of the Fourier amplitude spectra for analogue records. Only use records for periods within the passband of the filters applied.
- Exclude data from earthquakes with $M_w < 5$ because of risk of misallocating records to the wrong small events and because small events can be poorly located. Also records from earthquakes with $M_w < 5$ are unlikely to be of engineering significance.
- Cannot find negative anelastic coefficients for periods $> 1\,\mathrm{s}$ and therefore exclude this term for all periods.
- Try including a M^2 term but find that it is not statistically significant so remove it.
- Examine residuals (display graphs for 0.1 and $1\,\mathrm{s}$) w.r.t. M and R. Find no significant (at 5% level) trends.
- Examine histograms of residuals for 0.1 and $1\,\mathrm{s}$ and find that expected normal distribution fits the histograms closely.

4.169 Hong *et al.* (2009b)

- See Section 2.270.
- Response parameter is pseudo-acceleration for 5% damping.

4.170 Hong *et al.* (2009a)

- See Section 2.271.
- Response parameter is pseudo-acceleration for 5% damping.
- Only report coefficients for three periods (0.3, 1 and $3\,\mathrm{s}$).

4.171 Kuehn *et al.* (2009)

- See Section 2.272.
- Response parameter is pseudo-acceleration for 5% damping.
- Only use data up to highest usable period.
- Note that could choose different functional form for each period separate but believe effect would be small so use the same for all periods.

4.172 Moss (2009)

- See Section 2.274.
- Response parameter is pseudo-acceleration for 5% damping.
- Finds maximum decrease in σ is 9% at $3\,\mathrm{s}$.

4.173 Rodriguez-Marek & Montalva (2010)

- Ground-motion model is a simplified version of Boore & Atkinson (2008), because it is the simplest NGA functional form[11]:

$$
\begin{aligned}
\ln(\bar{y}) &= F_m + F_d + F_{site}(S_{surface}) + [F_{100}(S_{100}) + F_{200}(S_{200})](1 - S_{surface}) \\
F_d &= [c_1 + c_2(M - M_{ref})] \ln(R/R_{ref}) + c_3(R - R_{ref}) \\
R &= \sqrt{R^2 + h^2} \\
F_m &= e_1 + e_5(M - M_h) + e_6(M - M_h)^2 \quad \text{for} \quad M < M_h \\
F_m &= e_1 + e_7(M - M_h) \quad \text{for} \quad M > M_h \\
F_{site} &= b_{lin} \ln(V_{s,30}/V_{ref}) \\
F_{100} &= a_{100} + b_{100} \ln(V_{s,30}/V_{ref}) + c_{100} \ln(V_{s,hole}/3000) \\
F_{200} &= a_{200} + b_{200} \ln(V_{s,30}/V_{ref}) + c_{200} \ln(V_{s,hole}/3000)
\end{aligned}
$$

- Sites characterized by $V_{s,30}$, $V_{s,hole}$ (shear-wave velocity at depth of instrument), $S_{surface}$ (1 for surface record, 0 otherwise), S_{100} (1 for borehole record from $< 150\,\mathrm{m}$ depth, 0 otherwise) and S_{200} (1 for borehole record from $> 150\,\mathrm{m}$ depth, 0 otherwise).
- Response parameter is pseudo-acceleration for 5% damping.
- Use the same data as Cotton *et al.* (2008) (see Section 2.256).
- Develop GMPEs for use in the estimation of single-station σ.
- Note that functional form assumes that magnitude and distance dependency are the same for both surface and borehole records. Also assume that site amplification is linear, which note appears to be true for most records but not all but insufficient data to constrain nonlinearity using purely empirical method so ignore it.

[11]Number of typographic errors in report so this may not be correct functional form.

- For regression: use only surface data to constrain b_{lin}, use both surface and borehole records to compute inter-event σs and assume intra-event σs independent of magnitude. Note that final assumption is somewhat limiting but use residual analysis to examine dependency of intra-event terms on depth, $V_{s,30}$ and magnitude.
- Compute single-station σs based on residuals from the 44 stations that recorded ≥ 15 earthquakes. Averaged these 44 σs to obtain a single estimate of single-station σ. Note that more work on these σs is being undertaken. Find single-station σs are on average 25% lower than total σ. Find that total σs obtained for borehole stations lower than those at surface but the single-station σs are not considerable different on the surface and in boreholes.

4.174 Rupakhety & Sigbjörnsson (2009)

- See Section 2.276.
- Response parameter is acceleration for 5% damping.
- Also provide coefficients for constant-ductility inelastic spectral ordinates and structural behaviour factors for application within Eurocode 8.
- Coefficients only reported for 29 periods — graphs for rest.
- Note that coefficients are not smooth functions w.r.t. period, which is undesirable for practical purposes. Smooth coefficients using Savitzky-Golay procedure with a span of 19 and a quadratic polynomial and then recomputed σ. Verify that smoothing does not disturb inherent correlation between model parameters by comparing correlation matrix of coefficients before and after smoothing. Find that smoothing has little effect on matrix nor on σ.

4.175 Sharma *et al.* (2009)

- Ground-motion model is:

$$\log A = b_1 + b_2 M_w + b_3 \log \sqrt{R_{JB}^2 + b_4^2} + b_5 S + b_6 H$$

- Response parameter is acceleration for 5% damping.
- Use two site classes:

$S = 1$ Rock. 69 records.

$S = 0$ Soil. 132 records.

- Focal depths between 5 and $33\,\mathrm{km}$ for Iranian events and 19 and $50\,\mathrm{km}$ for Indian earthquakes.
- Use two fault mechanisms:

$H = 0$ Reverse. 8 earthquakes and 123 records.

$H = 1$ Strike-slip. 8 earthquakes and 78 records.

- Seek to develop model for Indian Himalayas. Due to lack of near-source data from India include data from the Zagros region of Iran, which has comparable seismotectonics (continental compression). Note that some differences, in particular the higher dip angles of reverse events in the Zagros compared to those in the Himalayas.
- Use data from three strong-motion arrays in Indian Himalayas: Kangra array in Himachal Pradesh, Uttar Pradesh and Shillong array in Meghalaya and Assam, and from Iran Strong-Motion Network. Note that records from at least three significant Himalayan earthquakes have not yet been digitized.
- Use some non-Zagros data from Iran because of similar focal mechanisms and since no significant difference in ground motions between these events are those in the Zagros was observed.
- Note that data seems to be adequate between $M_w 5$ and 7 and up to $100\,\mathrm{km}$.
- To exclude data from earthquakes that show anomalous behaviour, the PGAs for each earthquake individually were plotted against distance. Find that decay rates for 6/2/1988 and 14/3/1998 earthquakes were different than rest so data from these events were excluded.
- Also exclude data from two earthquakes (6/8/1988, 10/1/1990 and 6/5/1995) due to their great hypocentral depths ($> 90\,\mathrm{km}$).
- Also exclude data from eight earthquakes (9/1/1990, 24/3/1995, 14/12/2005, 29/11/2006, 10/12/2006, 9/6/2007, 18/10/2007 and 25/11/2007) because no focal mechanisms published.
- Prefer r_{jb} partly because of lack of reliable depths for most Himalayan earthquakes.
- Estimate r_{jb} for some earthquakes by using reported focal mechanism and relationships of Wells & Coppersmith (1994).
- Use explicit weighting method of Campbell (1981) with equal weights given to records falling into three ranges: $\leq 10\,\mathrm{km}$, 10–$100\,\mathrm{km}$ and more than $100\,\mathrm{km}$.
- Note that high standard deviations partly due to low quality of site information, large uncertainties in source-to-site distances and simple functional form.

4.176 Akkar & Bommer (2010)

- See Section 2.277.
- Response parameter is pseudo-acceleration for 5% damping.
- Derive equations up to $4\,\mathrm{s}$ but only report coefficients to $3\,\mathrm{s}$ because of a significant drop in available data at this period and because of the related issue of a sudden change in σ (particularly intra-event σ) at $3.2\,\mathrm{s}$.

4.177 Akkar & Çağnan (2010)

- See Section 2.278.
- Response parameter is pseudo-acceleration for 5% damping.
- Data become scarce for $T > 2\,\mathrm{s}$ due to cut-off frequencies used and, therefore, do not derive equations for longer periods. Limit of $0.03\,\mathrm{s}$ is based on Nyquist (sampling rates are generally $\geq 100\,\mathrm{Hz}$) and high-cut filtering used (generally $> 30\,\mathrm{Hz}$). Note that this conservative choice is based on the study of Douglas & Boore (2011).

4.178 Ghodrati Amiri *et al.* (2010)

- Ground-motion model is:

$$\log(\mathrm{SA}) = C_1 + C_2 M_s + C_3 \log(R)$$

- Use two site classes that are consistent with Iranian design code and derive equations for each separately:

  Soil $V_s < 375\,\mathrm{m/s}$.

  Rock $V_s > 375\,\mathrm{m/s}$.

- Response parameter is acceleration for 5% damping.
- Focal depths between 5 and $59\,\mathrm{km}$ but most $10\,\mathrm{km}$.
- Based on Ghodrati Amiri *et al.* (2007a) (see Section 2.236) but using larger and reappraised dataset.
- Derive models for Zagros and Alborz-Central Iran separately.
- Note the poor quality of some Iranian strong-motion data. Selected data based on accuracy of independent parameters.
- State that faulting mechanism is known for only a small proportion of data. Therefore, it is not considered.
- Use M_s because it is the most common scale for Iranian earthquakes.
- Most data from $M_s < 6.5$ and $5 < r_{hypo} < 200\,\mathrm{km}$. Note lack of near-source data from $M_s > 6$.
- Because of small and moderate size of most earthquakes used and since causative faults are not known for many earthquakes use r_{hypo}, which compute using S-P method because of uncertainty in reported hypocentral locations.
- Data from SMA-1 (about 210 records on soil and 130 on rock) and SSA-2 (about 220 records on soil and 170 on rock).
- Bandpass filter records using cut-off frequencies chosen based on instrument type and data quality. Cut-offs chosen by trial and error based on magnitude and distance of record and obtained velocity. Generally cut-offs are: 0.15–$0.20\,\mathrm{Hz}$ and 30–$33\,\mathrm{Hz}$ for SSA-2 on rock, 0.15–$0.25\,\mathrm{Hz}$ and 20–$23\,\mathrm{Hz}$ for SMA-1 on rock, 0.07–$0.20\,\mathrm{Hz}$ and 30–$33\,\mathrm{Hz}$ for SSA-2 on soil and 0.15–$0.20\,\mathrm{Hz}$ and 20–$23\,\mathrm{Hz}$ for SMA-1 on soil.

- Choose functional form after many tests (not shown) and because it is simple but physically justified.
- Note that predictions show peaks and valleys since no smoothing applied.
- Report that residual analysis (not shown) shows predictions are unbiased w.r.t. magnitude, distance and site conditions.

4.179 Arroyo *et al.* (2010)

- See Section 2.279.
- Response parameter is pseudo-acceleration for 5% damping.

4.180 Bindi *et al.* (2010)

- See Section 2.280.
- Response parameter is acceleration for 5% damping.

4.181 Douglas & Halldórsson (2010)

- See Section 2.282.
- Response parameter is acceleration for 5% damping.

4.182 Faccioli *et al.* (2010)

- See Section 2.283.
- Response parameter is displacement for 5% damping.
- Coefficients only given for a subset of periods for which analysis conducted.
- Site terms particularly important for $T \geq 0.25\,\mathrm{s}$, where reduction in σ is between 5% and 15%.

4.183 Hong & Goda (2010)

- See Section 2.285.
- Response parameter is pseudo-acceleration for 5% damping.
- Present correlation models between ground motions at different periods.

4.184 Jayaram & Baker (2010)

- See Section 2.286.
- Response parameter is pseudo-acceleration for 5% damping.
- Report coefficients only for $1\,\mathrm{s}$.

4.185 Montalva (2010)

- See Section 2.287.
- Response parameter is pseudo-acceleration for 5% damping.
- Residual analysis shown for 0.03, 0.2, 0.6, 1.0 and $1.4\,\mathrm{s}$.

4.186 Ornthammarath *et al.* (2010), Ornthammarath (2010) & Ornthammarath *et al.* (2011)

- See Section 2.288.
- Response parameter is acceleration for 5% damping.

4.187 Sadeghi *et al.* (2010)

- Ground-motion model is:

$$\begin{aligned}
\log A &= a(f) + b(f)M - c_1(f)\log R - k(f)R \quad \text{for} \quad R \leq R_1 \\
\log A &= a(f) + b(f)M - c_1(f)\log R_1 - c_2(f)\log(R/R_1) - k(f)R \quad \text{for} \quad R_1 < R \leq R_2 \\
\log A &= a(f) + b(f)M - c_1(f)\log R_1 - c_2(f)\log(R_2/R_1) - c_3(f)\log(R/R_2) - k(f)R \\
&\quad \text{for} \quad R > R_2
\end{aligned}$$

  Functional form chosen to enable modelling of effect of reflections off Moho and surface wave attenuation.

- Use two site classes:

  Soil $V_{s,30} < 750\,\mathrm{m/s}$ or, for 30 stations classified using H/V ratios, $f_0 < 7.5\,\mathrm{Hz}$ where f_0 is peak frequency. 556 records.

  Rock $V_{s,30} > 750\,\mathrm{m/s}$ or , for 30 stations classified using H/V ratios, $f_0 > 7.5\,\mathrm{Hz}$. 213 records.

  Develop models for all data and only soil records.

- Data from 573 different stations.
- Response parameter is acceleration for 5% damping.
- Also develop separate models for regions of Alborz (20 earthquakes and 423 records), Zagros (27 earthquakes and 198 records), East (32 earthquakes and 262 records) and Central South (20 earthquakes and 175 records). Note that regionalization is limited by lack of data for other regions.

- Use data recorded by National Strong Motion Network of Iran from 1987 to 2007.
- Select data by criterion of earthquake having being recorded by ≥ 3 stations within $350\,\mathrm{km}$.
- Most data from $M_w < 6.5$ and $r < 150\,\mathrm{km}$.
- Insufficient data to constrain model for $R > R_2$ therefore set geometric spreading coefficient to 0.5.
- Use Monte Carlo technique to find coefficients.
- Fit a and b to functional forms: $a_1 + a_2 \exp(-a_3 T)$ and $b_1 + b_2 T + b_3 T^2 + b_4 T^3$ respectively. Also present model assuming $a = a_1 + a_2 T + a_3 T + a_4 T^3$.
- Plot residuals against r_{epi}.
- Believe model can be applied for $5 < M < 7.5$ and $r_{epi} < 200\,\mathrm{km}$.

4.188 Saffari *et al.* (2010)

- Ground-motion model is:

$$\log A = a(T) M_w - \log[X + d(T) 10^{0.5 M_w}] - b(T) X + c_{Rock} L_R + c_{Soil} L_S$$

- Use two site classes:

Rock $L_R = 1$, $L_S = 0$.

Soil $L_S = 1$, $L_R = 0$.

- Focal depths between 7 and $72\,\mathrm{km}$ with most between 10 and $30\,\mathrm{km}$.
- Response parameter is acceleration for 5% damping.
- Use data from Iranian Strong-Motion Network run by Building and Housing Research Centre.
- Select data based on these criteria: $M_w \geq 5$, record on ground surface (free-field) and two orthogonal horizontal components available. Apply a M_w-dependent distance filter. After first regression data again truncated based on the median plus one σ model and a trigger level of $10\,\mathrm{gal}$.
- Examine data binned by M_w w.r.t. distance and remove earthquakes with irregular distributions (due to tectonic or other reasons).
- Baseline correct and bandpass filter (cut-offs of 0.2 and $20\,\mathrm{Hz}$) data based on characteristics of instruments (SSA-2 and SMA-1).
- Use rock data to define all coefficients and then compute c_{Soil} and σ_{Soil} using soil data and the coefficients defined from rock data (details not given).
- Smooth coefficients using fifth-degree polynomial based on logarithm of period.
- Derive coefficients for central Iran and Zagros separately.

Chapter 5

General characteristics of GMPEs for spectral ordinates

Table 2 gives the general characteristics of published attenuation relations for spectral ordinates. The columns are the same as in Table 1 with three extra columns:

Ts Number of periods for which attenuation equations are derived

$T_{\rm min}$ Minimum period for which attenuation equation is derived

$T_{\rm max}$ Maximum period for which attenuation equation is derived

Illustration 2: Characteristics of published spectral relations

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Johnson (1973)	W. USA	41	-	23	5.3	7.7	m_b	6.3	149.8	r_{epi}	1	14	0.055	2.469	M	1	A
Kobayashi & Nagahashi (1977)	Japan	U	-	U	5.4*	7.9*	U	60*	210*	r_{hypo}	I	U	0.1	5	R[1]	O	A
McGuire (1977)	W. USA	34	-	22	5.3	7.6	M_L	14	125	r_{hypo}	1	16	0.1	8	B	U	A
Trifunac (1977) & Trifunac & Anderson (1977)	W. USA	182	182	46	3.8	7.7	Mostly M_L	6[2]*	400[3]*	r_{epi}	3	91	0.04	12	B	O	A
Faccioli (1978)	W. USA, Japan, Papua New Guinea, Mexico & Greece	26[4]	-	11	5.3	7.8	U	15	342	r_{hypo}	1	15	0.1	4	B	U	A
McGuire (1978)	W. USA	70	-	17+*	4.5*	7.7	U[5]	11*	210*	r_{hypo}	2	1	1	1	B	U	A
Trifunac (1978) & Trifunac & Anderson (1978a)	W. USA	182	182	46	3.8	7.7	Mostly M_L	6[6]*	400[7]*	r_{epi}	3	91	0.04	12	B	O	A
Trifunac & Anderson (1978b)	W. USA	182	182	46	3.8	7.7	Mostly M_L	6[8]*	400[9]*	r_{epi}	3	91	0.04	12	B	O	A

continued on next page

[1] They state it is two dimensional response spectrum which assume to be resolved component.
[2] Note only valid for $R \geq 20\,\mathrm{km}$
[3] Note only valid for $R \leq 200\,\mathrm{km}$
[4] Total earthquake components (does not need to be multiplied by two)
[5] Idriss (1978) finds magnitudes to be mixture of M_L, m_b and M_s.
[6] Note only valid for $R \geq 20\,\mathrm{km}$
[7] Note only valid for $R \leq 200\,\mathrm{km}$
[8] Note only valid for $R \geq 20\,\mathrm{km}$
[9] Note only valid for $R \leq 200\,\mathrm{km}$

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Cornell *et al.* (1979)	W. USA	70	-	U	U	U	M_L	U	U	r_{hypo}	1	7	0.17	5	C	U	A
Faccioli & Agalbato (1979)	Friuli, Italy	38	-	14	3.7	6.3	M_L	5 (r_{epi})	190 (r_{epi})	r_{hypo}	2	1	1	1	B	1	A
Trifunac & Lee (1979)	W. N. America	U	U	U	U	U	U	U	U	r_{epi}	3	91	0.04	15	U	U	A
Ohsaki *et al.* (1980b)	Japan	95	-	29+	3.9*	7.2*	U	3*	500*	r_{hypo}	2	86	0.02	5	U	1	A
Ohsaki *et al.* (1980a)	Japan	75	-	U	4	7.4	U	6	500	r_{hypo}	1	U	0.02	5	U	1	A
Trifunac (1980)	W. USA	U	-	U	U	U	U	U	U	r_{epi}	C	91	0.04	7.5	U	U	A
Devillers & Mohammadioun (1981)	W. USA	186	-	U	3.3*	7.7*	U	$\geq$ 10	250*	r_{hypo}	1	46	0.04	10	U	1	A
Joyner & Boore (1982a)	W. N. America	64	-	12	5.3*	7.7	M_w	0.6*	110*	r_{jb}	2	12	0.1	4	L	2	A
Joyner & Boore (1982b)	W. N. America	64	-	12	5.3*	7.7	M_w	0.6*	110*	r_{jb}	2	12	0.1	4	L, R	2	A
Kobayashi & Midorikawa (1982)	Japan	45	-	U	5.1	7.5	U	50	280	r_{hypo}	1	U	0.1	5	U	O	A
Joyner & Fumal (1984), Joyner & Fumal (1985) & Joyner & Boore (1988)	W. N. America	U	-	U	5.0	7.7	$M_w(M_L)$	U	U	r_{jb}	C	12	0.1	4	L	U	A
Kawashima *et al.* (1984)	Japan	197	-	90	5.0	U	M_{JMA}	U	U	r_{epi}	3	10	0.1	3	R	1	A
Kawashima *et al.* (1985)	Japan	-	119	90*	5.0*	7.5*	M_{JMA}	5*	500*	r_{epi}	3	10	0.1	3	-	1	A
Trifunac & Lee (1985)	W. N. America	438	438	104	U	U	U	U	U	r_{hypo}	3, C	91	0.04	15	U	U	A

continued on next page

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Kamiyama & Yanagisawa (1986)	Japan	228	-	69	4.5	7.9	M_{JMA}	3	323	r_{epi}	I	45	0.1	10	U	1	A
C.B. Crouse (1987)[10]	S. California	U	-	U	U	U	M_s	U	U	r_{rup}	1	10	0.05	6	B	U	A
Lee (1987) & Lee (1993)	Mostly California	494	494	106	U	U	M_L for $M \lesssim 6.5$, others for $M > 6.5$	U	U	r_{epi}	3	91	0.04	15	B	U	A
K. Sadigh (1987)[11]	W. USA + others	U	-	U	U	U	M_w	U	U	r_{rup}	2	7	0.1	4	B	U	A (S, R)
Annaka & Nozawa (1988)	Japan	U	-	45	U	U	U	U	U	U	1	U	0.04*	4*	U	1	A
Crouse *et al.* (1988)	N. Honshu	64	-	U	5.1	8.2	M_w, M_s & M_{JMA} for < 7.5	42	407	r_E, r_{hypo} for $M < 7.5$	1	10	0.1	4	B	1	A
Petrovski & Marcellini (1988)	Europe	120	120	46	3	7	U	8	200	r_{hypo}	1	26	0.02	5	L	1	A
Yokota *et al.* (1988)	Tokyo	154	24	75 (U)	4.0	6.1	M_{JMA}	59 (60)	206 (100)	r_{hypo}	1	U	0.1 (0.05)	10 (5)	U	U	A
Youngs *et al.* (1988)	Worldwide subduction zones	20 + 197 + 389	-	16* (60)	5.6* (5)	8.1* (8.1, 8.2)[12]	M_w (M_s, m_b)	U (15*, 20*)	U (450*, 450*)	r_{rup}, r_{hypo} for $M_w \lesssim 7.5$	1	15	0.07	4	G	1W	A (B,F)
Kamiyama (1989)	Japan	228	-	U	4.1	7.9	M_{JMA}	3	350	r_{epi}	I	U	0.05*	10*	U	1	A
Trifunac & Lee (1989)	Mostly California	438	438	104	U	U	U	U	U	r_{epi}	C	12	0.04	14	B	U	A

continued on next page

[10] Reported in Joyner & Boore (1988).
[11] Reported in Joyner & Boore (1988).
[12] Consider equations valid for $M_w \leq 8$

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Atkinson (1990)	E. N. America + 10 others	92+10[13]	-	8+3	3.60 (5.16)	6.00 (6.84)	M_w	8 (8)	1215 (23)	r_{hypo}	1	4	0.1	1	B	2	A
Campbell (1990)	Unknown	U	-	U	U	U	M_L for $M < 6$, M_s for $M \geq 6$	U	U	r_{seis}	1	15	0.04	4	U	U	A
Dahle *et al.* (1990b) & Dahle *et al.* (1990a)	Worldwide intraplate regions	87	-	56	2.9	7.8	M_s (M_L, m_b, M_{CL}	6	1300	r_{hypo}	1	89	0.025	4	L	2	A
Tamura *et al.* (1990)	Japan	97	-	7	7.1	7.9	M_{JMA}	U	U	r_{epi}	3	13	2	20	L	1, O	A
Tsai *et al.* (1990)	Worldwide	<88	-	<51	4.9*	7.4	M_w	3*	150*	r_{rup}	1	14	0.07	1	U	M	T (S,O)
Crouse (1991)	Worldwide subduction zones	235	-	U	5.1	8.2	M_w (M_s, M_{JMA})	>8	>469	r_E, r_{hypo} for $M < 7.5$	1	10	0.1	4	B	1	A
Dahle *et al.* (1991)	Intraplate (particularly Norway)	395+31	-	136+11	2.4*(4.1)	5.2*(6.9)	M_s (M_L,M_{CL})	20* (9.7)	1200* (1300)	r_{hypo}	1	4[14]	0.1	1	L	O	A
I.M. Idriss (1991)[15]	Unknown	572	-	30*	4.6	7.4	M_L for $M < 6$, M_s for $M \geq 6$	1	100	r_{rup}, r_{hypo} for $M < 6$	1	23	0.03	5	U	U	A
Loh *et al.* (1991)	Taiwan	112	-	63	4.0	7.1	M_L	5.0	178.3	r_{hypo}	1	11	0.04	10	L	U	A
Matuschka & Davis (1991)	New Zealand	80	80	30	U	U	U	U	U	U	3	16	0.04	4	B	U	A

continued on next page

[13] Total earthquake components (does not need to be multiplied by two). 79+10 records for $0.1\,\mathrm{s}$ equation.
[14] Consider more than 4 natural periods but results not reported.
[15] Reported in Idriss (1993).

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Mohammadioun (1991)	Italy	144	-	46	3.0	6.5	U	6	186	r_{hypo}, 1 eq. with r_{rup}	1	81	0.013	1.95	B	U	A
Stamatovska & Petrovski (1991)	Mainly Italy and former Yugoslavia	489[16]	-	78	3*	8*	M_L	10*	500*	r_{hypo}	1	23	0.05	5	B	1	A
Niazi & Bozorgnia (1992)	SMART-1 array, Taiwan	236	234	12	3.6	7.8	M_L (M_D) for $M_L < 6.6$, else M_s	3.1[17]	119.7[17]	r_{hypo}	1	23	0.03	10	M	2W	A
Benito *et al.* (1992)	Campano Lucano	84	-	U	4.7	6.5	M_L	3.4*	142*	r_{hypo}	3	15	0.04	10	L	1	A
Silva & Abrahamson (1992)	W. USA with 4 foreign	U–136	-	U–12	6.1	7.4	M_w	3*	100*	r_{seis}	2	10	1	20	G	1M	A (S,R)
Tento *et al.* (1992)	Italy	137	-	40	4	6.6	M_L	3.2	170	r_{jb} for $M_L \geq 5.7$, r_{epi} otherwise	1	12	0.04	2.75	L	2	A
Abrahamson & Silva (1993)	W. USA with 4 foreign	22–201	-	1–18	6.0	7.4	M_w	0.6*	100*	r_{rup}	2	10	1	20	G	1M	A (S, R)
Boore *et al.* (1993) & Boore *et al.* (1997)	W. N. America	112	-	14	5.30	7.70	M_w	0	109	r_{jb}	3	46	0.1	2	L, G	2M	A
Caillot & Bard (1993)	Italy	83	-	≤ 40	3.2	6.8	M_s if M_L & $M_s \geq 6.0$ else M_L	10	63	r_{hypo}	2	25	0.05	1.98	U	2, 1W	A

continued on next page

[16] Does not need to be multiplied by two.
[17] Distance to centre of array

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Campbell (1993)	Worldwide	U	-	U	U[18]	U	M_L for $M < 6.0$ and M_s otherwise	U	U[19]	r_{seis}	2	15	0.04	4	M	O	A (T,S)
Sadigh *et al.* (1993) & Sadigh *et al.* (1997)	California with 4 foreign	960+4	U	119+2	3.8 (6.8)	7.4 (7.4)	M_w	0.1 (3)	305 (172)[20]	r_{rup} for some, r_{hypo} for small ones	2	21	0.05[21]	7.5[22]	G	U	A(R,S)
Electric Power Research Institute (1993a)	Eastern North America	66	132	U	4*	6.8*	M_w, m_{Lg}	5*	1000*	r_{hypo} (r_{rup} for largest)	3	10	0.03	1	G	1M	A
Sun & Peng (1993)	W. USA with 1 foreign	150+1	-	42+1	4.1	7.7	M_L for $M < 6$, else M_s	2*	150*	r_{epi}	C	U	0.04	10	R	1	A
Boore *et al.* (1994a) & Boore *et al.* (1997)	W. N. America	112 (70)	-	14 (9)	5.30	7.70 (7.40)	M_w	0	109	r_{jb}	C	46	0.1	2	L, G	1M, 2M	A (R,S)[23]
Climent *et al.* (1994)	Central America & Mexico	280	U	72	U	U	U	U	U	U	U	U	0.05*	≥ 2	U	U	A
Fukushima *et al.* (1994) & Fukushima *et al.* (1995)	3 vertical arrays in Japan	285	284	42	5.0	7.7	M_{JMA}	60*	400*	r_{hypo}	I	U	0.05	2	B	1,2	A
Lawson & Krawinkler (1994)	W. USA	250+	-	11	5.8	7.4	M_w	U	100	r_{jb}	3	38	0.1	4	U	1M	A

continued on next page

[18] Considers equation valid for $M \geq 4.7$.
[19] Considers equation valid for $d \leq 300\,\mathrm{km}$.
[20] Equations stated to be for distances up to $100\,\mathrm{km}$
[21] Minimum period for vertical equations is $0.04\,\mathrm{s}$.
[22] Maximum period for vertical equations is $3\,\mathrm{s}$.
[23] Coefficients given in Boore *et al.* (1994b).

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Lee & Manić (1994) & Lee (1995)	Former Yugoslavia	313	313	183	3.75	7.0	U	4	250	r_{epi}	6	12	0.04	2	U	2R	A
Mohammadioun (1994a)	California	108[24]	56	23	5.3	7.7	M_L	3	136	Often r_{rup}, r_{hypo} in far field	1	96	0.013	5	B	1	A
Mohammadioun (1994b)	W. USA	530[25]	≈ 265	U	U	U	M_L	1	250	r_{rup}, r_E if more appropriate, r_{hypo} in far field	1	96	0.013	5	B	1	A
Musson *et al.* (1994)	UK + 28* foreign	88*+28*[26]	-	15+16	3 (3.7)	4.1 (6.4)	M_L	70* (>1.3)	>477.4 (200*)	r_{hypo}	1	4	0.1	1	U[27]	O	A
Theodulidis & Papazachos (1994)	Greece+16 foreign	105+16[28]	-	36+4	4.5 (7.2)	7.0 (7.5)	M_s, M_w, M_{JMA}	1 (48)	128 (236)	r_{epi}	2	73	0.05	5	B	O	A
Dahle *et al.* (1995)	Cen. America	280	-	72	3*	8*	M_w (M_s, m_b, M_D)	6*	490*	r_{hypo}	2	8	0.025	4	L	1B	A
Lee & Trifunac (1995)	W. N. America	1926	1926	297	1.7	7.7	Usually M_L for $M \leq 6.5$ and M_s for $M > 6.5$	2	200+	r_{hypo}	9, 3 × C	91	0.04	15	U	1	A
Ambraseys *et al.* (1996)	Europe & Mid. East	422	-	157	4.0	7.9	M_s (unspecified)	0	260	r_{jb} for $M > 6.0$, r_{epi} otherwise	3	46	0.1	2	L	2	A

continued on next page

[24] Total number, does not need to be multiplied by two.
[25] Total number, does not need to be multiplied by two.
[26] There are 116 records in total.
[27] Free (1996) believes it is largest horizontal component.
[28] Total number of components does not need to be multiplied by two

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Ambraseys & Simpson (1996)	Europe & Mid. East	-	417	157	4.0	7.9	M_s (unspecified)	0	260	r_{jb} for $M > 6.0$, r_{epi} otherwise	3	46	0.1	2	L	2	A
Bommer *et al.* (1996)	El Salvador & Nicaragua	36	-	20	3.7	7.0	M_s	62	260	r_{hypo}	1	10	0.1	2	L	U	A
Crouse & McGuire (1996)	Cen. & S. California	238	-	16	6.0	7.7	M_s	0.1	211	r_{rup}	4	14	0.04	14	G	1W	R,S (R,S)
Free (1996) & Free *et al.* (1998)	Stable continental regions	399–410	347–477	H: 137–138, V: 126–132	1.5	6.8	M_w	0	820	r_{jb} for some, r_{epi} for most	2	52	0.04	2	L	1	A
Molas & Yamazaki (1996)	Japan	2166	-	387	4.1	7.8	M_{JMA}	8*	1000*	r_{rup} for 2 earthquakes, r_{hypo} otherwise	I	12	0.1	4	L	O	A
Ohno *et al.* (1996)	California	248	-	17	5.0	7.5	M_w (M_L)	7.2	99.6	r_q for $M > 5.3$, r_{hypo} otherwise	2	U	0.02	2	B	2M	A
Sabetta & Pugliese (1996)	Italy	95	95	17	4.6	6.8	M_s if M_L & $M_s \geq 5.5$ else M_L	1.5, 1.5	179, 180[29]	Both r_{jb} & r_{epi}	3	14	0.04	4	L	1	A
Spudich *et al.* (1996) & Spudich *et al.* (1997)	Worldwide extensional regimes	99–118	-	27–29	5.10	6.90	M_w	0	102.1	r_{jb}	2	46	0.1	2	G, C	2M	NS
Abrahamson & Silva (1997)	California with some others	≤ 655*	≤ 650*	≤ 58	4.4	7.4	U	0.1	220*	r_{rup}	2	28	0.01	5	G	1M	A (S,O,T)

continued on next page

[29] State equations should not be used for distances $> 100\,\mathrm{km}$

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Atkinson (1997)	Cascadia with some foreign	U	-	11+9	4.1	6.7(8.2)	M_w	20*	580*	r_c for some, r_{hypo} for small ones	2	12	0.1	2	B	2	A
Campbell (1997), Campbell (2000) & Campbell (2001)	Worldwide	266 [30]	173	H:30, V:22	4.7	8.1	M_s for $M_s \geq 6$, M_L for $M_s < 6$	3	50	r_{seis}	3	13	0.05	4	G	IW	A (S,R,N)
Schmidt *et al.* (1997)	Costa Rica	200	-	57	3.3	7.6	M_w (M_s, m_b, M_D)	6.1	182.1	r_{hypo}	3	7	0.025	4	L, B	O	A
Youngs *et al.* (1997)	Worldwide subduction zones	≤ 476	-	≤ 164	5.0	8.2	M_w (M_s,m_b)	8.5	550.9	r_{rup}, r_{hypo} for some	2	11	0.075	3	G	1M	NT (N,T)
Bommer *et al.* (1998)	Europe & Mid. East	121–183	-	34–43	5.5	7.9	M_s	3	260	r_{jb} for most, r_{epi} otherwise	3	66	0.04	3	L	2	A
Perea & Sordo (1998)	Urban area of Puebla, Mexico	10 [31]	-	8	5.8	8.1	m_b for $M < 6$, M_s otherwise	274	663	r_{epi}	1	195	0.01	3.5	L	1	A
Reyes (1998)	University City, Mexico City	20+	-	20+	U	U	M_w	U	U	r_{rup}	I	2	1.0	3.0	S	U	A
Shabestari & Yamazaki (1998)	Japan	3990	-	1020	U	8.1	M_{JMA}	U	U	r_{rup}	U	35	0.04	10	L	O	A
Chapman (1999)	W. N. America	304	-	23	5.0	7.7	M_w	0.1	189.4	r_{jb}	3	24	0.1	2	G	2M	A

continued on next page

[30] Typographic error in Table 3 of Campbell (1997) does not match number of recordings in Table 4

[31] Typographical error in Figure 3b) of Perea & Sordo (1998) because it does not match their Table 1.

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Spudich *et al.* (1999)	Worldwide extensional regimes	105–132	-	$\leq$ 38	5.1	7.2	M_w	0	99.4	r_{jb}	2	46	0.1	2	G	1M	NS
Ambraseys & Douglas (2000), Douglas (2001b) & Ambraseys & Douglas (2003)	Worldwide	186	183	44	5.83	7.8	M_s	0	15	r_{jb}	3	46	0.1	2	L	1	A
Bozorgnia *et al.* (2000)	Worldwide	1308	1308	33	U	U	M_w	U	$\leq$ 60	r_{seis}	4	U	0.05	4	G	U	A (R,S,T)
Campbell & Bozorgnia (2000)	Worldwide	275–435	274–434	$\leq$ 36	$\geq$ 4.7	$\leq$ 7.7	M_w	$\geq$ 1*	$\leq$ 60*	r_{seis}	4	14	0.05	4	G	1	A (S,R,T)
Chou & Uang (2000)	California	273	-	15	5.6	7.4	M_w	0*	120	r_{jb}	3	25	0.1	3	G	2M	A
Field (2000)	S California	357–447	-	28	5.1	7.5	M_w	0	148.9	r_{jb}	C (6)	3	0.3	3.0	G	1M	A (R, S, O)
Kawano *et al.* (2000)	Japan	107	107	44	5.5	7.0	M_{JMA}	27	202	r_q	I, C	U	0.02	5	U	O	A
Kobayashi *et al.* (2000)	Japan	U	-	U	5.0	7.8	M_w	0.9*	400*	U	4	17	0.1	5	B	1M	A
McVerry *et al.* (2000)	NZ with 66 foreign	$\leq$ 224 (461+66)	-	(51+17)	(5.08)	(7.23(7.41))	M_w	(0.1)	(573)	(r_{rup} for some, r_c for most)	4	U	0.01*	4*	U	O	A (N, R, RO)
Monguilner *et al.* (2000b)	W. Argentina	54	54	10	4.3	7.4	M_s if M_L & $M_s > 6$, M_L otherwise	11	350	r_{hypo}	2	200	0.1	6	U	1W	A
Shabestari & Yamazaki (2000)	Japan	6017	-	94	5.0	6.6	M_{JMA}	7*	950*	r_{rup}	I	35	0.04	10	L	O	A
Smit *et al.* (2000)	Caucasus	84	-	26	4.0	7.1	M_s	4	230	r_{hypo}	1	22	0.05	1	L	2	A

continued on next page

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Takahashi *et al.* (2000)	Japan+166 foreign	≤1332	-	U+7*	5* (5.8*)	8.3* (8*)	M_w	1* (0.1*)	300* (100*)	r_{rup}, r_{hypo} for some	4	20	0.05	5	G	O	A
Lussou *et al.* (2001)	Japan	3011	3011	102	3.7	6.3	M_{JMA}	4*	600*	r_{hypo}	4	63	0.02	10	B	2	A
Das *et al.* (2002)	NE India	174	-	6	5.7*	7.2*	U	53.51*	153.91*	r_{hypo}	1	20	0.04	1	V	2	A
Gülkan & Kalkan (2002)	Turkey	93[32]	-	19	4.5	7.4	M_w	1.20	150	r_{jb}, r_{epi}	3	46	0.1	2	L, R	1	A
Khademi (2002)	Iran	160	160	28*	3.4*	7.4	M_w (m_b for $M_s < 5$ and M_s otherwise)	0.1*	180*	r_{jb}, r_{epi} for $M < 5.9$	2	13	0.05	4	L	O	A
Manic (2002)	Former Yugoslavia	153[33]	77	19	4.0 and 4.2	6.9 and 7.0	M_s and M_L	0 and 0	110 and 150	r_{jb} and r_{epi}	2	14	0.04	4	B	1	A
Schwarz *et al.* (2002)	N.W. Turkey	683	683	U	0.9*	7.2	M_L	0*	250*	r_{epi}	3	11	0.01	2	U	1	A
Zonno & Montaldo (2002)	Umbria-Marche	161	-	15	4.5	5.9	M_L	2*	100*	r_{epi}	2	14	0.04	4	L	2	N, O
Alarcón (2003)	Colombia	45 or 47	-	U	4.0	6.7	M_s	49.7	322.4	r_{hypo}	1	84	0.05	3	U	U	A
Atkinson & Boore (2003)	Subduction zones	1200+	-	43*	5.5	8.3	M_w	11*	550*	r_{rup}	4	7	0.04	3	C	1M	F, B
Berge-Thierry *et al.* (2003)	Europe & Mid. East+163 from W. USA	802+163[34]	403+82[35]	130+8	4.0 (5.8)	7.9 (7.4)	M_s (M_w for W. USA)	4	330	r_{hypo}	2	143	0.03	10	B	2	A

continued on next page

[32]This is total number of horizontal components used. They come from 47 triaxial records.
[33]This is total number of components. Does not need to be multiplied by two.
[34]Total number of records. Does not need to be multiplied by two.
[35]485 records in total but do not state number of vertical records from W. USA.

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Bommer *et al.* (2003)	Europe & Mid. East	422	-	157	4.0	7.9	M_s (unspecified)	0	260	r_{jb} for $M_s > 6.0$, r_{epi} otherwise	3	46	0.1	2	L	1M	A (S, R, N)
Campbell & Bozorgnia (2003d), Campbell & Bozorgnia (2003a) & Bozorgnia & Campbell (2004b)	Worldwide	443	439	36[36]	4.7	7.7	M_w	2*	60*	r_{seis}	4	14	0.05	4	G	1	A (S & N, R, T)
Fukushima *et al.* (2003)	Mainly west Eurasia+some US and Japanese	399+341	-	40+10	5.5	7.4	M_w (M_s)	0.5	235	r_{hypo} (r_{rup} for 2 earthquakes)	2	11	0.03	2	B	2	A
Kalkan & Gülkan (2004a)	Turkey	-	95–100[37]	47	4.2	7.4	M_w (unspecified scales)	1.2	250	r_{jb}, r_{epi} for small events	3	46	0.1	2	-	1	A
Kalkan & Gülkan (2004a)	Turkey	112	-	57	4.0	7.4	M_w (unspecified scales)	1.2	250.0	r_{jb}, r_{epi} for small events	3	46	0.1	2	L[38]	1	A
Matsumoto *et al.* (2004)	Japan	293[39]	-	63	5.0*	7.6*	M_{JMA}	0*	195*	r_{rup} & r_q	1	U	0.02*	4*	M	1M	A (B, C, F)
Özbey *et al.* (2004)	NW Turkey	195	-	17	5.0	7.4	M_w (M_L)	5*	300*	r_{jb}	3	31	0.10	4.0	G	1M	NS

continued on next page

[36] For horizontal corrected records. There are 34 for vertical corrected records.
[37] Authors do not state reason for different number of records used for different periods.
[38] The caption of their Table 2 states that reported coefficients are for mean.
[39] The authors also report that they used 139 'sets', which could refer to number of records rather than the 293 'components' that they also report.

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Pankow & Pechmann (2004) and Pankow & Pechmann (2006)	Worldwide extensional regimes	142	-	39	5.1	7.2	M_w	0	99.4	r_{jb}	2	46	0.1	2.0	G, O	1M	NS
Sunuwar *et al.* (2004)	Okhotsk-Amur plate boundary	667	667	42	4.0	5.6	M_{JMA}	>3	>264	r_{hypo}	1	19	0.05	3.0	L	2M	A
Takahashi *et al.* (2004)	Mainly Japan+W USA+Iran	4400	-	270	4.9*	8.3*	M_w	0.3*	300	r_{rup} for some, r_{hypo} for rest	4	21	0.02	5.0	G	1M	A (B, F, R, S)
Yu & Hu (2004)	W USA	522+187[40]	-	38+14*	5.0	7.5	M_s	1.5*	575*	r_{epi}	1	U	0.04	20	B	O	A
Ambraseys *et al.* (2005a)	Europe & Middle East	207–595	-	59–135	5.0	7.6	M_w	0	99	r_{jb} (r_{epi} for small events)	3	61	0.05	2.5	L	1M	A (N, T, S, O)
Ambraseys *et al.* (2005b)	Europe & Middle East	-	207–595	59–135	5.0	7.6	M_w	0	99	r_{jb} (r_{epi} for small events)	3	61	0.05	2.5	-	1M	A (N, T, S, O)
Bragato & Slejko (2005)	E Alps (45.6–$46.8°$N & 12–$14°$E)	1402	3168	240	2.5	6.3	M_L	0	130	r_{jb} & r_{epi}	1	47	0.05	2.0	R	O	A
García *et al.* (2005)	Central Mexico	277	277	16	5.2	7.4	M_w	4*	400*	r_{rup} for $M_w > 6.5$, r_{hypo} otherwise	1	15	0.04	5	G[41]	1M	B
McGarr & Fletcher (2005)	Central Utah coal-mining areas	31–72	-	12	0.98	4.2	M_w (M_{CL})	0.5*	10*	r_{hypo}	2	5	0.1	2.0	L	2M	M

continued on next page

[40] Does not need to be multiplied by two.

[41] Call it ‘quadratic mean’, which is assumed to be geometric mean.

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Pousse *et al.* (2005)	Japan	6812	-	591	4.1	7.3	M_w (M_{JMA})	5.5	303	r_{hypo} (r_{rup} for 10 events)	5	U	0.01	4.0	B	2	A
Takahashi *et al.* (2005), Zhao *et al.* (2006) and Fukushima *et al.* (2006)	Japan+208 overseas	2763–4518+208	-	<249+20	5.0	8.3	M_w	0*	300*	r_{rup}	5	20	0.05	5	G	1M	C (R, S/N) & F, B
Wald *et al.* (2005)	California	U	-	U	U	5.3*	M_w	U	U	r_{jb}	1	3	0.3	3	L	U	A
Atkinson (2006)	Los Angeles region	461–4973	-	509+	3.1*	7.1*	M_w	5*	350*	r_{epi} (r_{jb} for some)	3	0.3	3.0	I, C	B	1	A
Beyer & Bommer (2006)	Shallow crustal (USA, Taiwan, Turkey and others)	949	-	103	4.3*	7.9*	M_w	6*	200*	r_{hypo}	U	77	0.01	5.0	1, 2, A, B, C, D50, G, I50, L, N, P, R	1M	A (U)
Bindi *et al.* (2006)	Umbria-Marche	144–239	-	$\leq$ 45	4.0	5.9	M_L	1*	100*	r_{epi} & r_{hypo}	4	14	0.04	4	L	1M	NS
Campbell & Bozorgnia (2006a) and Campbell & Bozorgnia (2006b)	Worldwide	1500+	-	60+	4.2	7.9	M_w	0	200	r_{rup}	C	U	U	10	G	2M	A
Hernandez *et al.* (2006)	Haulien LSTT (Taiwan)	456	456	51	5	7.3	M_L	13.7	134.8	r_{hypo}	5	143	0.03	10	B	1	A

continued on next page

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Kanno *et al.* (2006)	Japan+some foreign	3205–3392+331–377 (shallow) & 7721–8150 (deep)	-	70–73+10 & 101–111	5.0* (6.1) & 5.5*	8.2* (7.4) & 8.0*	M_w (M_{JMA})	1* (1.5*) & 30*	450* (350*) & 450*	r_{rup} (r_{hypo} for some)	C	37	0.05	5	R	2M	A
McVerry *et al.* (2006)	New Zealand	435	-	49	5.08	7.09	M_w	6	400	r_c (r_{rup})	3	11	0.075	3	L, G	1M	C (R, OR, S & N) & F, B
Pousse *et al.* (2006)	Japan	9390[42]	-	U	4.1	7.3	(M_w)	5*	250*	r_{hypo} (r_{rup} for some)	5	U	0.01	3	B	2M	A
Sakamoto *et al.* (2006)	Japan	3198	-	52	5.5	8.3	M_w	1	300	r_{rup}	5	U	0.02	5	M	1M	A
Sharma & Bungum (2006)	Indian Himalayas+9 European records	175+9	-	12+7	4.5 (6.0)	7.2 (7.4)	M_w (m_b)	10	200	r_{hypo}	2	13	0.04	2.5	G	1W	A
Zare & Sabzali (2006)	Iran	89	89	55*	2.7	7.4	M_w	4	167	r_{hypo}	4	21	0.10	4	U	1M & 2M	A
Akkar & Bommer (2007b)	Europe & Middle East	532	-	131	5.0	7.6	M_w	0	99	r_{jb}	3	80	0.05	4	G	1WM	A (N, S, R)
Bindi *et al.* (2007)	NW Turkey	4047	4047	528	0.5	5.9	M_L[43]	5*	200*	r_{hypo}[44]	2	8	0.1	1[45]	L	1M	A
Bommer *et al.* (2007)	Europe and Middle East	997	-	289	3	7.6	M_w	0	99	r_{jb} (r_{epi} for small events)	3	10	0.05	0.50	G	1WM	A (N, S, R)

continued on next page

[42] Does not need to be multiplied by two.
[43] Also derive model using M_w.
[44] Also derive model using r_{epi}.
[45] Their Figure 2 present σs up to $2\,\mathrm{s}$ but the coefficients of the model are not given beyond $1\,\mathrm{s}$.

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Boore & Atkinson (2007) & Boore & Atkinson (2008)	Worldwide shallow crustal	600*–1574	-	18*–58	4.27–5.00[46]	7.90[47]	M_w	0	280[48]	r_{jb}	C	21	0.01	10	I50	2M	A (N, R, S, U)
Campbell & Bozorgnia (2007), Campbell & Bozorgnia (2008b) & Campbell & Bozorgnia (2008a)	Worldwide shallow crustal	506–1561	-	21–64	4.27[49]	7.90[50]	M_w	0.07	199.27	r_{rup}	C	21	0.01	10	I50	1M	A (N, R, S, HW)
Danciu & Tselentis (2007a) & Danciu & Tselentis (2007b)	Greece	335	-	151	4.5	6.9	M_w	0*	136	r_{epi}	3	31	0.10	4	A	1M	A (N, ST)
Fukushima *et al.* (2007b) & Fukushima *et al.* (2007a)	Mainly west Eurasia+some US and Japanese	399+339	-	40+10	5.5	7.4	M_w (M_s)	0.5	235	r_{hypo} (r_{rup} for 2 earthquakes)	5	U	0.03	3	B	2M	A
Hong & Goda (2007) & Goda & Hong (2008)	California	484–592	-	34–39	5*	7.4*	M_w	0.2*	100*	r_{jb}	C	27	0.1	3	G, Q, R	1M	A
Massa *et al.* (2007)	Central northern Italy	1063	-	243	2.5	5.2	M_L	0*	300*	r_{hypo}	2	8	0.1	1.5	L	1	A
Tejeda-Jácome & Chávez-García (2007)	Colima, Mexico	162	162	26	3.3	5.2	M_L	5*	175	r_{hypo}	1	H:10, V:9	0.07	H:0.99, V:0.80	G	2M	A

continued on next page

[46] Recommend that model is not extrapolated below 5 due to lack of data.

[47] Believe that model can be used to 8.0.

[48] Recommend that model is not used for distances $\geq 200\,\mathrm{km}$.

[49] Believe that model can be extrapolated down to 4.0.

[50] Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Abrahamson & Silva (2008) & Abrahamson & Silva (2009)	Worldwide shallow crustal	500*–2754	-	64–135	4.27[51]	7.9[52]	M_w	0.06*	200*	r_{rup}	C	22	0.01	10	I50	1M	A (N, R, S, HW)
Aghabarati & Tehranizadeh (2008)	Worldwide shallow crustal	646	646	54	5.2	7.9	M_w	0	60	r_{rup}	C	26	0.025	10	G	1M	A (N, R, S)
Cauzzi & Faccioli (2008) & Cauzzi (2008)	Worldwide shallow crustal	1164	1132	60	5.0	7.2	M_w	6*	150*	r_{hypo}	4 & C	400	0.05	20	G	2M	A (N, S, R)
Chen & Yu (2008b)	Worldwide shallow crustal	130	-	U	5.0*	7.5*	M_w	0*	200*	U	1	U	0.04	10	B	1	A
Chen & Yu (2008a)	Worldwide shallow crustal	130	-	U	5.0*	7.5*	M_w	0*	200*	U	1	U	0.04	10	B	1	A
Chiou & Youngs (2008)	Worldwide shallow crustal	≤1950[53]	-	≤125	4.265[54]	7.90[55]	M_w	0.2*[56]	70*[57]	r_{rup}	C	22	0.01	10	I50	1M	A (N, R, S, HW, AS)
Cotton *et al.* (2008)	Japan	3894	-	337	4	7.3	M_w (M_{JMA})	1	100	r_{rup} (r_{hypo} for small)	4[58] & 2[59]	23	0.01	3.33	G	2M	A
Dhakal *et al.* (2008)	Northern Japan	772 (B), 1749 (F)	-	10 (B), 20 (F)	5.4 (B), 5.1 (F)	7.0 (B), 7.3 (F)	M_w	70*	300*	r_{hypo}	1	16	0.1	5	V	2	B, F

continued on next page

[51] Recommend that model is not extrapolated below 5 due to lack of data.
[52] Believe that model can be reliably extrapolated to 8.5.
[53] Due to filtering number of records and earthquakes depends on period.
[54] Believe that model can be extrapolated down to 4.0.
[55] Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.
[56] Believe that model valid to $0\,\mathrm{km}$.
[57] Believe that model valid to $200\,\mathrm{km}$.
[58] For stations on surface.
[59] For borehole stations.

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Idriss (2008)	Worldwide shallow crustal	942	-	72	4.5	7.7	M_w	0.3	199.3	r_{rup}	2	31	0.01	10	I50	1	A (R/RO/NO, S/N)
Lin & Lee (2008)	NE Taiwan+10 foreign	4244+139	-	44+10	4.1 (6.0)	7.3 (8.1)	M_w (M_L)	15	630	r_{hypo}	2	27	0.01	5	G	1W	A (B, F)
Massa *et al.* (2008)	Northern Italy	306	306	82	3.5 & 4.0	6.3 & 6.5	M_w (M_L) & M_L	1*	100*	r_{epi}	3	12 & 14	0.04	2 & 4	L	1M	A
Morasca *et al.* (2008)	Molise	3090	3090	100	2.7	5.7	M_L	12*	60*	r_{hypo}	2	12	0.04	2	L	1M	A
Yuzawa & Kudo (2008)	Japan	1988	-	18	5.9, 5.7	8.0, 7.9	M_{JMA}, M_w	U	U	r_q	1	45	1	10	U	2	A
Ghasemi *et al.* (2009)	Iran+West Eurasia	716+177	-	200	5.0	7.4	M_w	0.5	100	r_{rup} (r_{hypo} for small events)	2	17	0.05	3	I50	1M	A
Aghabarati & Tehranizadeh (2009)	Worldwide shallow crustal	678	678	55	5.2	7.9	M_w	0	60	r_{rup}	C	26	0.025	10	G	1M	A (N, R, S)
Akyol & Karagöz (2009)	Western Anatolia	168	-	49	4.03	6.40	M_w (M_d, M_L)	15	200	r_{hypo}	2	30	0.05	2	L	2M	A
Bindi *et al.* (2009a)	Italy	241	241	27	4.8	6.9	M_w	0	190	r_{jb}	3	18	0.03	2	L, G	1M	A (N, S, R)
Bindi *et al.* (2009b)	Italy	235	-	27	4.6	6.9	M_w (M_L)	0	183	r_{jb}, r_{epi}	3	19	0.03	3	L	1M	A
Bragato (2009)	Italy	922	-	116	2.7	4.5	M_L	6	100	r_{epi}	I, 3, 1, C	3	0.3	3	U	1	A
Hong *et al.* (2009b)	Mexico (interface & inslab)	418, 277	-, -	40, 16	5.0, 5.2	8.0, 7.4	M_w	U	U	r_{rup} (r_{hypo} for small)	1	27	0.1	3	G, R, Q	1M	F, S

continued on next page

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Hong *et al.* (2009a)	California	484–592	-	34–39	5*	7.4*	M_w	0.2*	100*	r_{jb}	C	27	0.1	3	G, R	1M, 2M, O	A
Kuehn *et al.* (2009)	Worldwide	2660	-	60	5.61	7.9*	M_w	0.1*	200*	r_{jb}	C	39	0.01	3	G	1M (O)	A (N, R, S)
Moss (2009)	Worldwide shallow crustal	1950	-	125	4.265	7.90	M_w	0.2*	70*	r_{rup}	C	5	0.1	7.5	I50	1M	A (N, R, S, HW, AS)
Rupakhety & Sigbjörnsson (2009)	South Iceland+others	64+29	-	12	5.02	7.67	M_w	1	97	r_{jb} (r_{epi} for some)	2	66	0.04	2.5	L	1	S & O
Sharma *et al.* (2009)	Indian Himalayas+Zagros	58+143	-	6+10	5.5 & 5.9	6.8 & 6.6	M_w	5* & 10*	190* & 200*	r_{jb}	1	13	0.04	2.5	G	O	A (S, R)
Akkar & Bommer (2010)	Europe & Middle East	532	-	131	5.0	7.6	M_w	0	99	r_{jb}	3	60	0.05	3	G	1M	A (N, S, R)
Akkar & Çağnan (2010)	Turkey	433	-	137	5.0	7.6	M_w	0*	200*	r_{jb}	C	14	0.03	2	G	1M	A (N, S, R)
Ghodrati Amiri *et al.* (2010)	Alborz and central Iran[60]	416	-	189	3.2[61]	7.7	M_s (m_b)	5*	400*	r_{hypo}	2	15	0.1	4	L	1M	A
Arroyo *et al.* (2010)	Pacific coast of Mexico	418	-	40	5.0	8.0	M_w	20	400	r_{rup} (r_{hypo} for $M_w < 6$)	1	56	0.04	5	U	O	F
Bindi *et al.* (2010)	Italy	561	561	107	4.0	6.9	M_w	1*	100*	r_{jb}, r_{epi}	3	21	0.03	2	L	1M	A
Douglas & Halldórsson (2010)	Europe & Middle East	595	-	135	5.0	7.6	M_w	0	99	r_{jb} (r_{epi} for small events)	3	61	0.05	2.5	L	1WM	A (N, T, S, O, AS)

continued on next page

[60] Also develop models for the Zagros region of Iran using 309 records from 190 earthquakes.
[61] State that only use data with $M_s \geq 4$ but one earthquake in their Appendix A has $M_s 3.2$.

Illustration 2: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$r_{\min}$	$r_{\max}$	r scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Faccioli *et al.* (2010)	Worldwide shallow crustal	1499	-	≤ 60	4.5	7.6	M_w	0.2*	200*	r_{rup} (r_{hypo} for small)	4 & C	22	0.05	20	G	1M	A (N, R, S)
Hong & Goda (2010)	California[62]	484–592	-	34–39	5.0	7.28	M_w	0.2*	100*	r_{jb}	C	6	0.2	3	1, 2	1M	A
Jayaram & Baker (2010)	Worldwide shallow crustal	1561	-	64	4.27	7.90	M_w	0.07	199.27	r_{rup}	C	21	0.01	10	I50	O	A (N, R, S, HW)
Montalva (2010)	Japan	3894	-	337	4	7.3	M_w (M_{JMA})	1	100	r_{rup} (r_{hypo} for small)	C, I	21	0.0384	1.3622	G	O (1M)	A
Ornthammarath *et al.* (2010), Ornthammarath (2010) & Ornthammarath *et al.* (2011)	South Iceland	81	-	6	5.1	6.5	M_w	1*	80*	r_{jb} (r_{epi} for $M_w < 6$)	2	4	0.2	2	G	1M	S
Rodriguez-Marek & Montalva (2010)	Japan	3894	-	337	4	7.3	M_w (M_{JMA})	1	100	r_{rup} (r_{hypo} for small)	C	7	0.01	1.3622	G	2M	A
Sadeghi *et al.* (2010)	Iran	883	-	79	5	7.4*	M_w	0*	340*	r_{epi}	2	8	0.1	3	U	O	A
Saffari *et al.* (2010)	Central Iran & Zagros	627	-	110	5	7.4*	M_w	5*	200*	r_{rup} (r_{hypo} for $M_w < 6.5$)	2	19	0.05	5	U	2M	A

[62] Also derive models for inslab (273 records from 16 earthquakes) and interface (413 records from 40 earthquakes) Mexican earthquakes.

Chapter 6

List of other ground-motion models

Published ground-motion models for the prediction of PGA and/or response spectral ordinates that were derived by methods other than regression analysis on strong-motion data are listed below in chronological order.

Illustration 3: GMPEs derived based on simulated ground motions, often the stochastic method

Herrmann & Goertz (1981)	Eastern North America
Herrmann & Nuttli (1984)	Eastern North America
Boore & Atkinson (1987) and Atkinson & Boore (1990)	Eastern North America
Nuttli & Herrmann (1987)	Eastern North America
Toro & McGuire (1987)	Eastern North America
Electric Power Research Institute (1988)	Eastern North America
Boore & Joyner (1991)	Eastern North America
Bungum *et al.* (1992)	Intraplate regions
Electric Power Research Institute (1993b)	Central and eastern USA
Savy *et al.* (1993)	Central and eastern USA
Atkinson & Boore (1995) & Atkinson & Boore (1997a)	Eastern North America
Frankel *et al.* (1996) & Electric Power Research Institute (2004, Appendix B)	Central and eastern USA
Atkinson & Boore (1997b)	Cascadia subduction zone
Hwang & Huo (1997)	Eastern USA
Ólafsson & Sigbjörnsson (1999)	Iceland
Atkinson & Silva (2000)	California
Somerville *et al.* (2001)	Central and eastern USA
Toro & Silva (2001)	Central USA
Gregor *et al.* (2002b)	Cascadia subduction zone
Silva *et al.* (2002)	Central and eastern USA
Toro (2002)	Central and eastern USA
Megawati *et al.* (2003)	Sumatran subduction zone
Electric Power Research Institute (2004) (model clusters)	Central and eastern USA
Iyengar & Raghu Kanth (2004)	Peninsular India
Zheng & Wong (2004)	Southern China
Megawati *et al.* (2005)	Sumatran subduction zone
Motazedian & Atkinson (2005)	Puerto Rico

continued on next page

Illustration 3: *continued*

Nath *et al.* (2005)	Sikkim Himalaya
Atkinson & Boore (2006)	Eastern North America
Collins *et al.* (2006)	Intermountain West, USA
Raghu Kanth & Iyengar (2006, 2007)	Peninsular India
Megawati (2007)	Hong Kong
Tuluka (2007)	African Western Rift Valley
Carvalho (2008)	Portugal
Jin *et al.* (2008)[1]	Fujian region, China
Liang *et al.* (2008)	Southwest Western Australia
Sokolov *et al.* (2008)	Vrancea, Romania
Atkinson & Macias (2009)	Cascadia subduction zone
Kang & Jin (2009)[2]	Sichuan region, China
Somerville *et al.* (2009)	Australia
Hamzehloo & Bahoosh (2010)	Tehran region, Iran
Megawati & Pan (2010)	Sumatran subduction zone

Illustration 4: Complete (source, path and site terms) stochastic models that could be used within the stochastic method (e.g. Boore, 2003)

De Natale *et al.* (1988)	Campi Flegrei, Italy
Atkinson (1996)	Cascadia
Atkinson & Silva (1997)	California
Gusev *et al.* (1997)	Kamchatka
Sokolov (1997)	Northern Caucasus
Sokolov (1998)	Caucasus
Raoof *et al.* (1999)	Southern California
Malagnini & Herrmann (2000)	Umbria-Marche, Italy
Malagnini *et al.* (2000a)	Apennines, Italy
Malagnini *et al.* (2000b)	Central Europe
Sokolov *et al.* (2000)	Taiwan
Akinci *et al.* (2001)	Erzincan, Turkey
Parvez *et al.* (2001)	Himalaya
Junn *et al.* (2002)	South Korea
Malagnini *et al.* (2002)	Northeastern Italy
Bay *et al.* (2003)	Switzerland
Bodin *et al.* (2004)	Kachchh basin, India
Jeon & Herrmann (2004)	Utah and Yellowstone, USA
Halldorsson & Papageorgiou (2005)	Intraplate and interplate
Scognamiglio *et al.* (2005)	Eastern Sicily, Italy
Sokolov *et al.* (2005)	Vrancea, Romania

continued on next page

[1]This may be an empirical GMPE because it is based on broadband velocity records from which acceleration time-histories are generated by ‘real-time simulation’. This could just mean differentiation.

[2]This may be an empirical GMPE because it is based on broadband velocity records from which acceleration time-histories are generated by ‘real-time simulation’. This could just mean differentiation.

Illustration 4: *continued*

Akinci *et al.* (2006)	Marmara, Turkey
Allen *et al.* (2006)	Southwest Western Australia
Chung (2006)	Southwestern Taiwan
Morasca *et al.* (2006)	Western Alps
Malagnini *et al.* (2007)	San Francisco, USA
Meirova *et al.* (2008)	Israel
Zafarani *et al.* (2008)	Iran
Hao & Gaull (2009)	Perth, Australia

Illustration 5: GMPEs derived using the hybrid stochastic-empirical method (e.g. Campbell, 2003b)

Atkinson (2001)	Eastern North America
Abrahamson & Silva (2002)	Central and eastern USA
Campbell (2003b)	Eastern North America
Atkinson (2005)	Cascadia
Tavakoli & Pezeshk (2005)	Eastern North America
Douglas *et al.* (2006)	Southern Norway
Douglas *et al.* (2006)	Southern Spain
Campbell (2007)	Central and eastern USA

Illustration 6: GMPEs derived by converting equations for the prediction of macroseismic intensity to the prediction of PGA and response spectral ordinates

Battis (1981)	Eastern North America
Hasegawa *et al.* (1981)	Canada
Huo *et al.* (1992)	China
Malkawi & Fahmi (1996)	Jordan

Illustration 7: GMPEs derived using the referenced-empirical method (e.g. Atkinson, 2008) that adjusts coefficients of published GMPEs for one region to provide a better match to observations from another

Atkinson (2008)	Eastern North America
Scasserra *et al.* (2009)	Italy
Atkinson (2009, 2010)	Hawaii
Gupta (2010)	Indo-Burmese subduction zone

Illustration 8: Studies where one or more coefficients of previously published GMPEs are altered following additional analysis (completely new GMPEs are not derived in these studies)

Eberhart-Phillips & McVerry (2003)	New terms for McVerry *et al.* (2000)
Wang & Takada (2009)	Adjustment of Si & Midorikawa (1999, 2000) for stations HKD100 and CHB022
Chiou *et al.* (2010)	New terms for Chiou & Youngs (2008)
Zhao (2010)	New terms for Zhao *et al.* (2006)
Atkinson & Boore (2011)	New terms for Boore & Atkinson (2008), Atkinson & Boore (2006) and Atkinson (2008)

Illustration 9: Non-parametric ground-motion models, i.e. models without an associated close-form equation, which are more difficult to use within seismic hazard assessments

Schnabel & Seed (1973)	Western North America
Katayama (1982)	Japan
Anderson & Lei (1994)	Guerrero, Mexico
Lee *et al.* (1995)	California
Anderson (1997)	Guerrero, Mexico
Fajfar & Peruš (1997)	Europe & Middle East
Garcia & Romo (2006)	Subduction zones
Pathak *et al.* (2006)	India
Güllü & Erçelebi (2007)	Turkey
Ahmad *et al.* (2008)	Europe & Middle East
Günaydın & Günaydın (2008)	Northwestern Turkey
Cabalar & Cevik (2009)	Turkey
Peruš & Fajfar (2009, 2010)	Worldwide

Bibliography

Abdalla, J. A., Mohamedzein, Y. E.-A., & Wahab, A. A. 2001. Probabilistic seismic hazard assessment of Sudan and its vicinity. *Earthquake Spectra*, **17**(3).

Abrahamson, N., & Silva, W. 2008. Summary of the Abrahamson & Silva NGA ground-motion relations. *Earthquake Spectra*, **24**(1), 67–97.

Abrahamson, N., & Silva, W. 2009 (Aug). *Errata for "Summary of the Abrahamson and Silva NGA ground-motion relations" by Abrahamson, N. A. and W. J. Silva*. Published on PEER NGA website.

Abrahamson, N. A., & Litehiser, J. J. 1989. Attenuation of vertical peak acceleration. *Bulletin of the Seismological Society of America*, **79**(3), 549–580.

Abrahamson, N. A., & Shedlock, K. M. 1997. Overview. *Seismological Research Letters*, **68**(1), 9–23.

Abrahamson, N. A., & Silva, W. J. 1993. Attenuation of long period strong ground motions. *In: Proceedings of Conference of American Society of Mechanical Engineers*.

Abrahamson, N. A., & Silva, W. J. 1997. Empirical response spectral attenuation relations for shallow crustal earthquakes. *Seismological Research Letters*, **68**(1), 94–127.

Abrahamson, N. A., & Silva, W. J. 2002 (Sep). Hybrid model — empirical attenuation relations for central and eastern U.S. hard and soft rock and deep soil site conditions. *In: CEUS Ground Motion Project Workshop*. Not seen. Cited in Electric Power Research Institute (2004). Only a presentation. Never officially published.

Abrahamson, N. A., & Youngs, R. R. 1992. A stable algorithm for regression analyses using the random effects model. *Bulletin of the Seismological Society of America*, **82**(1), 505–510.

Aghabarati, H., & Tehranizadeh, M. 2008. Near-source attenuation relationship for the geometric mean horizontal component of peak ground acceleration and acceleration response spectra. *Asian Journal of Civil Engineering (Building and Housing)*, **9**(3), 261–290.

Aghabarati, H., & Tehranizadeh, M. 2009. Near-source ground motion attenuation relationship for PGA and PSA of the vertical and horizontal components. *Bulletin of Earthquake Engineering*, **7**(3), 609–635.

Ágústsson, K., Þorbjarnardóttir, B., & Vogfjörð, K. 2008 (Apr). *Seismic wave attenuation for earthquakes in SW Iceland: First results*. Tech. rept. 08005. Veðurstofa Íslands (Icelandic Meteorological Office).

Ahmad, I., El Naggar, M. H., & Khan, A. N. 2008. Neural network based attenuation of strong motion peaks in Europe. *Journal of Earthquake Engineering*, **12**(5), 663–680.

Akinci, A., Malagnini, L., Herrmann, R. B., Pino, N. A., Scognamiglio, L., & Eyidogan, H. 2001. High-frequency ground motion in the Erzincan region, Turkey: Inferences from small earthquakes. *Bulletin of the Seismological Society of America*, **91**(6), 1446–1455.

Akinci, A., Malagnini, L., Herrmann, R. B., Gok, R., & Sørensen, M. B. 2006. Ground motion scaling in the Marmara region, Turkey. *Geophysical Journal International*, **166**(2), 635–651.

Akkar, S., & Bommer, J. J. 2006. Influence of long-period filter cut-off on elastic spectral displacements. *Earthquake Engineering and Structural Dynamics*, **35**(9), 1145–1165.

Akkar, S., & Bommer, J. J. 2007a. Empirical prediction equations for peak ground velocity derived from strong-motion records from Europe and the Middle East. *Bulletin of the Seismological Society of America*, **97**(2), 511–530.

Akkar, S., & Bommer, J. J. 2007b. Prediction of elastic displacement response spectra in Europe and the Middle East. *Earthquake Engineering and Structural Dynamics*, **36**(10), 1275–1301.

Akkar, S., & Bommer, J. J. 2010. Empirical equations for the prediction of PGA, PGV and spectral accelerations in Europe, the Mediterranean region and the Middle East. *Seismological Research Letters*, **81**(2), 195–206.

Akkar, S., & Çağnan, Z. 2010. A local ground-motion predictive model for Turkey and its comparison with other regional and global ground-motion models. *Bulletin of the Seismological Society of America*, **100**(6), 2978–2995.

Akkar, S., Çağnan, Z., Yenier, E., Erdoğan, Ö, Sandıkkaya, A., & Gülkan, P. 2010. The recently compiled Turkish strong-motion database: Preliminary investigation for seismological parameters. *Journal of Seismology*, **14**(3), 457–479.

Akyol, N., & Karagöz, Ö. 2009. Empirical attenuation relationships for western Anatolia, Turkey. *Turkish Journal of Earth sciences*, **18**, 351–382.

Alarcón, J. E. 2003. Relaciones de atenuación a partir de espectros de respuesta para Colombia. *In: Proceedings of the Second Colombian Conference on Earthquake Engineering*. In Spanish.

Alarcón, J. E. 2007 (Apr). *Estimation of duration, number of cycles, peak ground velocity, peak ground acceleration and spectral ordinates for engineering design*. Ph.D. thesis, University of London.

Alchalbi, A., Costa, G., & Suhadolc, P. 2003 (Aug). Strong motion records from Syria: A preliminary analysis. *In: Skopje Earthquake 40 Years of European Earthquake Engineering (SE-40EEE)*.

Alfaro, C. S., Kiremidjian, A. S., & White, R. A. 1990. *Seismic zoning and ground motion parameters for El Salvador*. Tech. rept. 93. The John A. Blume Earthquake Engineering Center, Stanford University. Not seen. Reported in Bommer *et al.* (1996).

Algermissen, S. T., Hansen, S. L., & Thenhaus, P. C. 1988. *Seismic hazard evaluation for El Salvador*. Tech. rept. Report for the US Agency for International Development. Not seen. Reported in Bommer *et al.* (1996).

Allen, T. I., Dhu, T., Cummins, P. R., & Schneider, J. F. 2006. Empirical attenuation of ground-motion spectral amplitudes in southwestern Western Australia. *Bulletin of the Seismological Society of America*, **96**(2), 572–585.

Aman, A., Singh, U. K., & Singh, R. P. 1995. A new empirical relation for strong seismic ground motion for the Himalayan region. *Current Science*, **69**(9), 772–777.

Ambraseys, N. 1975a. Ground motions in the near field of small-magnitude earthquakes. *Pages 113–136 of: Proceedings of the Commission on the Safety of Nuclear Installations, Organisation of Economic Cooperation in Europe*, vol. 1. Not seen. Reported in Ambraseys (1978a).

Ambraseys, N., & Douglas, J. 2000 (Aug). *Reappraisal of the effect of vertical ground motions on response*. ESEE Report 00-4. Department of Civil and Environmental Engineering, Imperial College, London.

Ambraseys, N., Smit, P., Berardi, R., Rinaldis, D., Cotton, F., & Berge, C. 2000. *Dissemination of European Strong-Motion Data*. CD-ROM collection. European Commission, Directorate-General XII, Environmental and Climate Programme, ENV4-CT97-0397, Brussels, Belgium.

Ambraseys, N. N. 1975b. Trends in engineering seismology in Europe. *Pages 39–52 of: Proceedings of Fifth European Conference on Earthquake Engineering*, vol. 3.

Ambraseys, N. N. 1978a. Middle East — a reappraisal of seismicity. *The Quarterly Journal of Engineering Geology*, **11**(1), 19–32.

Ambraseys, N. N. 1978b. Preliminary analysis of European strong-motion data 1965–1978. *Bulletin of the European Association of Earthquake Engineering*, **4**, 17–37.

Ambraseys, N. N. 1990. Uniform magnitude re-evaluation of European earthquakes associated with strong-motion records. *Earthquake Engineering and Structural Dynamics*, **19**(1), 1–20.

Ambraseys, N. N. 1995. The prediction of earthquake peak ground acceleration in Europe. *Earthquake Engineering and Structural Dynamics*, **24**(4), 467–490.

Ambraseys, N. N., & Bommer, J. J. 1991. The attenuation of ground accelerations in Europe. *Earthquake Engineering and Structural Dynamics*, **20**(12), 1179–1202.

Ambraseys, N. N., & Bommer, J. J. 1992. On the attenuation of ground accelerations in Europe. *Pages 675–678 of: Proceedings of Tenth World Conference on Earthquake Engineering*, vol. 2.

Ambraseys, N. N., & Bommer, J. J. 1995. Attenuation relations for use in Europe: An overview. *Pages 67–74 of:* Elnashai, A. S. (ed), *Proceedings of Fifth SECED Conference on European Seismic Design Practice*.

Ambraseys, N. N., & Douglas, J. 2003. Near-field horizontal and vertical earthquake ground motions. *Soil Dynamics and Earthquake Engineering*, **23**(1), 1–18.

Ambraseys, N. N., & Simpson, K. A. 1996. Prediction of vertical response spectra in Europe. *Earthquake Engineering and Structural Dynamics*, **25**(4), 401–412.

Ambraseys, N. N., & Srbulov, M. 1994. Attenuation of earthquake-induced ground displacements. *Earthquake Engineering and Structural Dynamics*, **23**(5), 467–487.

Ambraseys, N. N., Bommer, J. J., & Sarma, S. K. 1992 (Nov). *A review of seismic ground motions for UK design*. ESEE Report 92-8. Department of Civil Engineering, Imperial College, London.

Ambraseys, N. N., Simpson, K. A., & Bommer, J. J. 1996. Prediction of horizontal response spectra in Europe. *Earthquake Engineering and Structural Dynamics*, **25**(4), 371–400.

Ambraseys, N. N., Smit, P., Douglas, J., Margaris, B., Sigbjörnsson, R., Ólafsson, S., Suhadolc, P., & Costa, G. 2004. Internet site for European strong-motion data. *Bollettino di Geofisica Teorica ed Applicata*, **45**(3), 113–129.

Ambraseys, N. N., Douglas, J., Sarma, S. K., & Smit, P. M. 2005a. Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the Middle East: Horizontal peak ground acceleration and spectral acceleration. *Bulletin of Earthquake Engineering*, **3**(1), 1–53.

Ambraseys, N. N., Douglas, J., Sarma, S. K., & Smit, P. M. 2005b. Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the Middle East: Vertical peak ground acceleration and spectral acceleration. *Bulletin of Earthquake Engineering*, **3**(1), 55–73.

Anderson, J. G. 1997. Nonparametric description of peak acceleration above a subduction thrust. *Seismological Research Letters*, **68**(1), 86–93.

Anderson, J. G., & Lei, Y. 1994. Nonparametric description of peak acceleration as a function of magnitude, distance, and site in Guerrero, Mexico. *Bulletin of the Seismological Society of America*, **84**(4), 1003–1017.

Annaka, T., & Nozawa, Y. 1988. A probabilistic model for seismic hazard estimation in the Kanto district. *Pages 107–112 of: Proceedings of Ninth World Conference on Earthquake Engineering*, vol. **II**.

Aptikaev, F., & Kopnichev, J. 1980. Correlation between seismic vibration parameters and type of faulting. *Pages 107–110 of: Proceedings of Seventh World Conference on Earthquake Engineering*, vol. 1.

Arroyo, D., García, D., Ordaz, M., Mora, M. A., & Singh, S. K. 2010. Strong ground-motion relations for Mexican interplate earthquakes. *Journal of Seismology*, **14**(4), 769–785.

Atkinson, G. M. 1990. A comparison of eastern North American ground motion observations with theoretical predictions. *Seismological Research Letters*, **61**(3–4), 171–180.

Atkinson, G. M. 1996. The high-frequency shape of the source spectrum for earthquakes in eastern and western Canada. *Bulletin of the Seismological Society of America*, **86**(1A), 106–112.

Atkinson, G. M. 1997. Empirical ground motion relations for earthquakes in the Cascadia region. *Canadian Journal of Civil Engineering*, **24**, 64–77.

Atkinson, G. M. 2001. An alternative to stochastic ground-motion relations for use in seismic hazard analysis in eastern North America. *Seismological Research Letters*, **72**, 299–306.

Atkinson, G. M. 2005. Ground motions for earthquakes in southwestern British Columbia and northwestern Washington: Crustal, in-slab, and offshore events. *Bulletin of the Seismological Society of America*, **95**(3), 1027–1044.

Atkinson, G. M. 2006. Single-station sigma. *Bulletin of the Seismological Society of America*, **96**(2), 446–455.

Atkinson, G. M. 2008. Ground-motion prediction equations for eastern North America from a referenced empirical approach: Implications for epistemic uncertainty. *Bulletin of the Seismological Society of America*, **98**(3), 1304–1318.

Atkinson, G. M. 2009 (Mar). *Ground motion prediction equations for Hawaii from a referenced empirical approach*. Final technical report 08HQGR0020.

Atkinson, G. M. 2010. Ground motion prediction equations for Hawaii from a referenced empirical approach. *Bulletin of the Seismological Society of America*, **100**(2), 751–761.

Atkinson, G. M., & Boore, D. M. 1990. Recent trends in ground motion and spectral response relations for North America. *Earthquake Spectra*, **6**(1), 15–35.

Atkinson, G. M., & Boore, D. M. 1995. Ground-motion relations for eastern North America. *Bulletin of the Seismological Society of America*, **85**(1), 17–30.

Atkinson, G. M., & Boore, D. M. 1997a. Some comparisons between recent ground-motion relations. *Seismological Research Letters*, **68**(1).

Atkinson, G. M., & Boore, D. M. 1997b. Stochastic point-source modeling of ground motions in the Cascadia region. *Seismological Research Letters*, **68**(1), 74–85.

Atkinson, G. M., & Boore, D. M. 2003. Empirical ground-motion relations for subduction zone earthquakes and their application to Cascadia and other regions. *Bulletin of the Seismological Society of America*, **93**(4), 1703–1729.

Atkinson, G. M., & Boore, D. M. 2006. Earthquake ground-motion prediction equations for eastern North America. *Bulletin of the Seismological Society of America*, **96**(6), 2181–2205.

Atkinson, G. M., & Boore, D. M. 2011. Modifications to existing ground-motion prediction equations in light of new data. *Bulletin of the Seismological Society of America*, **101**(3). In press.

Atkinson, G. M., & Macias, M. 2009. Predicted ground motions for great interface earthquakes in the Cascadia subduction zone. *Bulletin of the Seismological Society of America*, **99**(3), 1552–1578.

Atkinson, G. M., & Silva, W. 1997. An empirical study of earthquake source spectra for California earthquakes. *Bulletin of the Seismological Society of America*, **87**(1), 97–113.

Atkinson, G. M., & Silva, W. 2000. Stochastic modeling of California ground motion. *Bulletin of the Seismological Society of America*, **90**(2), 255–274.

Aydan, Ö. 2007. Inference of seismic characteristics of possible earthquakes and liquefaction and landslide risks from active faults. *Pages 563–574 of: The 6th National Conference on Earthquake Engineering of Turkey*, vol. 1. Not seen. In Turkish.

Aydan, Ö., Sedaki, M., & Yarar, R. 1996. The seismic characteristics of Turkish earthquakes. *In: Proceedings of Eleventh World Conference on Earthquake Engineering*. Paper no. 1270.

Baag, C.-E., Chang, S.-J., Jo, N.-D., & Shin, J.-S. 1998. Evaluation of seismic hazard in the southern part of Korea. *In: Proceedings of the second international symposium on seismic hazards and ground motion in the region of moderate seismicity*. Not seen. Reported in Nakajima *et al.* (2007).

Battis, J. 1981. Regional modification of acceleration attenuation functions. *Bulletin of the Seismological Society of America*, **71**(4), 1309–1321.

Bay, F., Fäh, D., Malagnini, L., & Giardini, D. 2003. Spectral shear-wave ground-motion scaling in Switzerland. *Bulletin of the Seismological Society of America*, **93**(1), 414–429.

Beauducel, F., Bazin, S., & Bengoubou-Valerius, M. 2004 (Dec). *Loi d'atténuation B-cube pour l'évaluation rapide des intensités sismiques probables dans l'archipel de Guadeloupe*. Internal report OVSG-IPGP-UAG. Observatoire Volcanologique et Sismologique de Guadeloupe.

Benito, B., Rinaldis, D., Gorelli, V., & Paciello, A. 1992. Influence of the magnitude, distance and natural period of soil in the strong ground motion. *Pages 773–779 of: Proceedings of Tenth World Conference on Earthquake Engineering*, vol. 2.

Benito, B., Cabañas, L., Jiménez, M. E., Cabañas, C., López, M., Gómez, P., & Alvarez, S. 2000. Caracterización del movimiento del suelo en emplazamientos de la península ibérica y evaluación del daño potencial en estructuras. proyecto daños. *In:* Consejo de Seguridad Nuclear (ed), *Monografia ref. 19.2000*. In Spanish. Not seen.

Berge-Thierry, C., Cotton, F., Scotti, O., Griot-Pommera, D.-A., & Fukushima, Y. 2003. New empirical response spectral attenuation laws for moderate European earthquakes. *Journal of Earthquake Engineering*, **7**(2), 193–222.

Beyaz, T. 2004. *Development of a new attenuation relationship of seismic energy for Turkey using the strong motion records free of soil effect*. Ph.D. thesis, Ankara University, Turkey. Not seen. Reported in Selcuk *et al.* (2010).

Beyer, K., & Bommer, J. J. 2006. Relationships between median values and between aleatory variabilities for different definitions of the horizontal component of motion. *Bulletin of the Seismological Society of America*, **96**(4A), 1512–1522.

Bindi, D., Luzi, L., Pacor, F., Franceshina, G., & Castro, R. R. 2006. Ground-motion predictions from empirical attenuation relationships versus recorded data: The case of the 1997Ű-1998 Umbria-Marche, central Italy, strong-motion data set. *Bulletin of the Seismological Society of America*, **96**(3), 984–1002.

Bindi, D., Parolai, S., Grosser, H., Milkereit, C., & Durukal, E. 2007. Empirical ground-motion prediction equations for northwestern Turkey using the aftershocks of the 1999 Kocaeli earthquake. *Geophysical Research Letters*, **34**(L08305).

Bindi, D., Luzi, L., & Pacor, F. 2009a. Interevent and interstation variability computed for the Italian Accelerometric Archive (ITACA). *Bulletin of the Seismological Society of America*, **99**(4), 2471–2488.

Bindi, D., Luzi, L., Pacor, F., Sabetta, F., & Massa, M. 2009b. Towards a new reference ground motion prediction equation for Italy: Update of the Sabetta-Pugliese (1996). *Bulletin of Earthquake Engineering*, **7**(3), 591–608.

Bindi, D., Luzi, L., Massa, M., & Pacor, F. 2010. Horizontal and vertical ground motion prediction equations derived from the Italian Accelerometric Archive (ITACA). *Bulletin of Earthquake Engineering*, **8**(5), 1209–1230.

Blume, J. A. 1977. The SAM procedure for site-acceleration-magnitude relationships. *Pages 416–422 of: Proceedings of Sixth World Conference on Earthquake Engineering*, vol. I.

Blume, J. A. 1980. Distance partitioning in attenuation studies. *Pages 403–410 of: Proceedings of Seventh World Conference on Earthquake Engineering*, vol. 2.

Boatwright, J., Bundock, H., Luetgert, J., Seekins, L., Gee, L., & Lombard, P. 2003. The dependence of PGA and PGV on distance and magnitude inferred from northern California ShakeMap data. *Bulletin of the Seismological Society of America*, **93**(5), 2043–2055.

Bodin, P., Malagnini, L., & Akinci, A. 2004. Ground-motion scaling in the Kachchh basin, India, deduced from aftershocks of the 2001 $M_w 7.6$ Bhuj earthquake. *Bulletin of the Seismological Society of America*, **94**(5), 1658–1669.

Bolt, B. A., & Abrahamson, N. A. 1982. New attenuation relations for peak and expected accelerations of strong ground motion. *Bulletin of the Seismological Society of America*, **72**(6), 2307–2321.

Bommer, J. J. 2006. Empirical estimation of ground motion: Advances and issues. *Pages 115–135 of: Proceedings of Third International Symposium on the Effects of Surface Geology on Seismic Motion*. Paper number: KN 8.

Bommer, J. J., & Alarcón, J. E. 2006. The prediction and use of peak ground velocity. *Journal of Earthquake Engineering*, **10**(1), 1–31.

Bommer, J. J., & Martínez-Pereira, A. 1999. The effective duration of earthquake strong motion. *Journal of Earthquake Engineering*, **3**(2), 127–172.

Bommer, J. J., & Scherbaum, F. 2008. The use and misuse of logic trees in probabilistic seismic hazard analysis. *Earthquake Spectra*, **24**(4), 997–1009.

Bommer, J. J., Hernández, D. A., Navarrete, J. A., & Salazar, W. M. 1996. Seismic hazard assessments for El Salvador. *Geofísica Internacional*, **35**(3), 227–244.

Bommer, J. J., Elnashai, A. S., Chlimintzas, G. O., & Lee, D. 1998 (Mar). *Review and development of response spectra for displacement-based seismic design*. ESEE Report 98-3. Department of Civil Engineering, Imperial College, London.

Bommer, J. J., Douglas, J., & Strasser, F. O. 2003. Style-of-faulting in ground-motion prediction equations. *Bulletin of Earthquake Engineering*, **1**(2), 171–203.

Bommer, J. J., Stafford, P. J., Alarcón, J. E., & Akkar, S. 2007. The influence of magnitude range on empirical ground-motion prediction. *Bulletin of the Seismological Society of America*, **97**(6), 2152–2170.

Bommer, J. J., Stafford, P. J., & Alarcón, J. E. 2009. Empirical equations for the prediction of the significant, bracketed, and uniform duration of earthquake ground motion. *Bulletin of the Seismological Society of America*, **99**(6), 3217–3233.

Bommer, J. J., Douglas, J., Scherbaum, F., Cotton, F., Bungum, H., & Fäh, D. 2010. On the selection of ground-motion prediction equations for seismic hazard analysis. *Seismological Research Letters*, **81**(5), 783–793.

Boore, D. M. 1983. Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra. *Bulletin of the Seismological Society of America*, **73**(6), 1865–1894.

Boore, D. M. 2003. Simulation of ground motion using the stochastic method. *Pure and Applied Geophysics*, **160**(3–4), 635–676.

Boore, D. M. 2004. Estimating $vs30$ (or NEHRP site classes) from shallow velocity models (depths $\leq 30\,\mathrm{m}$). *Bulletin of the Seismological Society of America*, **94**(2), 591Ű–597.

Boore, D. M. 2005. Erratum: Equations for estimating horizontal response spectra and peak acceleration from western north american earthquakes: A summary of recent work. *Seismological Research Letters*, **76**(3), 368–369.

Boore, D. M., & Atkinson, G. M. 1987. Stochastic prediction of ground motion and spectral response parameters at hard-rock sites in eastern North America. *Bulletin of the Seismological Society of America*, **77**(22), 440–467.

Boore, D. M., & Atkinson, G. M. 2007. *Boore-Atkinson NGA ground motion relations for the geometric mean horizontal component of peak and spectral ground motion parameters*. PEER Report 2007/01. Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley.

Boore, D. M., & Atkinson, G. M. 2008. Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between $0.01\,\mathrm{s}$ and $10.0\,\mathrm{s}$. *Earthquake Spectra*, **24**(1), 99–138.

Boore, D. M., & Joyner, W. B. 1982. The empirical prediction of ground motion. *Bulletin of the Seismological Society of America*, **72**(6), S43–S60. Part B.

Boore, D. M., & Joyner, W. B. 1991. Estimation of ground motion at deep-soil sites in eastern North America. *Bulletin of the Seismological Society of America*, **81**(6), 2167–2185.

Boore, D. M., Joyner, W. B., & Fumal, T. E. 1993. *Estimation of response spectra and peak accelerations from western North American earthquakes: An interim report*. Open-File Report 93-509. U.S. Geological Survey. 70 pages.

Boore, D. M., Joyner, W. B., & Fumal, T. E. 1994a. *Estimation of response spectra and peak accelerations from western North American earthquakes: An interim report. Part 2*. Open-File Report 94-127. U.S. Geological Survey.

Boore, D. M., Joyner, W. B., & Fumal, T. E. 1994b. *Ground motion estimates for strike- and reverse-slip faults*. Provided to the Southern California Earthquake Center and widely distributed as an insert in Boore *et al.* (1994a). Not seen. Reported in Boore *et al.* (1997).

Boore, D. M., Joyner, W. B., & Fumal, T. E. 1997. Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work. *Seismological Research Letters*, **68**(1), 128–153.

Boore, D. M., Watson-Lamprey, J., & Abrahamson, N. A. 2006. Orientation-independent measures of ground motion. *Bulletin of the Seismological Society of America*, **96**(4A), 1502–1511.

Borcherdt, R. D. 1994. Estimates of site-dependent response spectra for design (methodology and justification). *Earthquake Spectra*, **10**(4), 617–653.

Bouhadad, Y., Laouami, N., Bensalem, R., & Larbes, S. 1998. Seismic hazard estimation in the central Tell Atlas of Algeria (Algiers-Kabylia). *In: Proceedings of Eleventh European Conference on Earthquake Engineering*.

Bozorgnia, Y., & Campbell, K. W. 2004a. Engineering characterization of ground motion. *Chap. 5 of:* Bozorgnia, Y., & Bertero, V. (eds), *Earthquake Engineering: From Engineering Seismology to Performance-Based Engineering*. Boca Raton, FL: CRC Press.

Bozorgnia, Y., & Campbell, K. W. 2004b. The vertical-to-horizontal response spectral ratio and tentative procedures for developing simplified V/H and the vertical design spectra. *Journal of Earthquake Engineering*, **8**(2), 175–207.

Bozorgnia, Y., Niazi, M., & Campbell, K. W. 1995. Characteristics of free-field vertical ground motion during the Northridge earthquake. *Earthquake Spectra*, **11**(4), 515–525.

Bozorgnia, Y., Campbell, K. W., & Niazi, M. 2000. Observed spectral characteristics of vertical ground motion recorded during worldwide earthquakes from 1957 to 1995. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper No. 2671.

Bragato, P. L. 2004. Regression analysis with truncated samples and its application to ground-motion attenuation studies. *Bulletin of the Seismological Society of America*, **94**(4), 1369–1378.

Bragato, P. L. 2005. Estimating an upper limit probability distribution for peak ground acceleration using the randomly clipped normal distribution. *Bulletin of the Seismological Society of America*, **95**(6), 2058–2065.

Bragato, P. L. 2009. Assessing regional and site-dependent variability of ground motions for ShakeMap implementation in Italy. *Bulletin of the Seismological Society of America*, **99**(5), 2950–2960.

Bragato, P. L., & Slejko, D. 2005. Empirical ground-motion attenuation relations for the eastern Alps in the magnitude range 2.5–6.3. *Bulletin of the Seismological Society of America*, **95**(1), 252–276.

Brillinger, D. R., & Preisler, H. K. 1984. An exploratory analysis of the Joyner-Boore attenuation data. *Bulletin of the Seismological Society of America*, **74**(4), 1441–1450.

Brillinger, D. R., & Preisler, H. K. 1985. Further analysis of the Joyner-Boore attenuation data. *Bulletin of the Seismological Society of America*, **75**(2), 611–614.

Bungum, H., Dahle, A., Toro, G., McGuire, R., & Gudmestad, O.T. 1992. Ground motions from intraplate earthquakes. *Pages 611–616 of: Proceedings of Tenth World Conference on Earthquake Engineering*, vol. 2.

Cabalar, A. F., & Cevik, A. 2009. Genetic programming-based attenuation relationship: An application of recent earthquakes in Turkey. *Computers & Geosciences*, **35**, 1884–1896.

Cabañas, L., Benito, B., Cabañas, C, López, M., Gómez, P., Jiménez, M. E., & Alvarez, S. 1999. Banco de datos de movimiento fuerte del suelo mfs. aplicaciones. *Pages 111–137 of:* Complutense (ed), *Física de la tierra*, vol. 11. In Spanish with English abstract.

Cabañas, L., Lopez, M., Benito, B., & Jiménez, M. E. 2000 (Sep). Estimation of PGA attenuation laws for Spain and Mediterranean region. Comparison with other ground motion models. *In: Proceedings of the XXVII General Assembly of the European Seismological Commission (ESC)*.

Caillot, V., & Bard, P. Y. 1993. Magnitude, distance and site dependent spectra from Italian accelerometric data. *European Earthquake Engineering*, **VII**(1), 37–48.

Campbell, K. W. 1981. Near-source attenuation of peak horizontal acceleration. *Bulletin of the Seismological Society of America*, **71**(6), 2039–2070.

Campbell, K. W. 1985. Strong motion attenuation relations: A ten-year perspective. *Earthquake Spectra*, **1**(4), 759–804.

Campbell, K. W. 1989. The dependence of peak horizontal acceleration on magnitude, distance, and site effects for small-magnitude earthquakes in California and eastern North America. *Bulletin of the Seismological Society of America*, **79**(5), 1311–1346.

Campbell, K. W. 1990 (Sep). *Empirical prediction of near-source soil and soft-rock ground motion for the Diablo Canyon power plant site, San Luis Obispo county, California*. Tech. rept. Dames & Moore, Evergreen, Colorado. Prepared for Lawrence Livermore National Laboratory. Not seen. Reported in Idriss (1993).

Campbell, K. W. 1993 (Jan). Empirical prediction of near-source ground motion from large earthquakes. *In: Proceedings of the International Workshop on Earthquake Hazard and Large Dams in the Himalaya*. Indian National Trust for Art and Cultural Heritage, New Delhi, India.

Campbell, K. W. 1997. Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra. *Seismological Research Letters*, **68**(1), 154–179.

Campbell, K. W. 2000. Erratum: Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra. *Seismological Research Letters*, **71**(3), 352–354.

Campbell, K. W. 2001. Erratum: Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra. *Seismological Research Letters*, **72**(4), 474.

Campbell, K. W. 2003a. Engineering models of strong ground motion. *Chap. 5 of:* Chen, W. F., & Scawthorn, C. (eds), *Handbook of Earthquake Engineering*. Boca Raton, FL, USA: CRC Press.

Campbell, K. W. 2003b. Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America. *Bulletin of the Seismological Society of America*, **93**(3), 1012–1033.

Campbell, K. W. 2003c. Strong-motion attenuation relations. *Chap. 60 of:* Lee, W. H. K., Kanamori, H., Jennings, P. C., & Kisslinger, C. (eds), *International Handbook of Earthquake and Engineering Seismology*. London: Academic Press.

Campbell, K. W. 2007 (Sep). *Validation and update of hybrid empirical ground motion (attenuation) relations for the CEUS*. Final technical report. ABS Consulting, Inc. (EQECAT), Beaverton, USA. NEHRP External Grants Program, U.S. Geological Survey Award Number: 05HQGR0032.

Campbell, K. W., & Bozorgnia, Y. 1994 (Jul). Near-source attenuation of peak horizontal acceleration from worldwide accelerograms recorded from 1957 to 1993. *Pages 283–292 of: Proceedings of the Fifth U.S. National Conference on Earthquake Engineering*, vol. III.

Campbell, K. W., & Bozorgnia, Y. 2000 (Nov). New empirical models for predicting near-source horizontal, vertical, and V/H response spectra: Implications for design. *In: Proceedings of the Sixth International Conference on Seismic Zonation*.

Campbell, K. W., & Bozorgnia, Y. 2003a. Erratum: Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. *Bulletin of the Seismological Society of America*, **93**(3), 1413.

Campbell, K. W., & Bozorgnia, Y. 2003b. Erratum: Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. *Bulletin of the Seismological Society of America*, **93**(4), 1872.

Campbell, K. W., & Bozorgnia, Y. 2003c. Erratum: Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. *Bulletin of the Seismological Society of America*, **94**(6), 2417.

Campbell, K. W., & Bozorgnia, Y. 2003d. Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. *Bulletin of the Seismological Society of America*, **93**(1), 314–331.

Campbell, K. W., & Bozorgnia, Y. 2006a (Apr). Campbell-Bozorgnia Next Generation Attenuation (NGA) relations for PGA, PGV and spectral acceleration: A progress report. *In: Proceedings of the Eighth U.S. National Conference on Earthquake Engineering*. Paper no. 906.

Campbell, K. W., & Bozorgnia, Y. 2006b (Sep). Next Generation Attenuation (NGA) empirical ground motion models: Can they be used in Europe? *In: Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*. Paper no. 458.

Campbell, K. W., & Bozorgnia, Y. 2007. *Campbell-Bozorgnia NGA ground motion relations for the geometric mean horizontal component of peak and spectral ground motion parameters*. PEER Report 2007/02. Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley.

Campbell, K. W., & Bozorgnia, Y. 2008a. Empirical ground motion model for shallow crustal earthquakes in active tectonic environments developed for the NGA project. *In: Proceedings of Fourteenth World Conference on Earthquake Engineering*. Paper no. 03-02-0004.

Campbell, K. W., & Bozorgnia, Y. 2008b. NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to $10\,\mathrm{s}$. *Earthquake Spectra*, **24**(1), 139–171.

Carvalho, A. 2008. *Modelação estocástica da acção sísmica em Portugal continental*. Ph.D. thesis, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal. In Portuguese. Not seen.

Cauzzi, C., & Faccioli, E. 2008. Broadband (0.05 to $20\,\mathrm{s}$) prediction of displacement response spectra based on worldwide digital records. *Journal of Seismology*, **12**(4), 453–475.

Cauzzi, C., Faccioli, E., Paolucci, R., & Villani, M. 2008. Long-period ground motion evaluation from a large worldwide digital strong motion database. *In: Proceedings of Fourteenth World Conference on Earthquake Engineering*. Paper no. S10-047.

Cauzzi, C. V. 2008 (Apr). *Broadband empirical prediction of displacement response spectra based on worldwide digital records*. Ph.D. thesis, Politecnico di Milano.

Chang, T.-Y., Cotton, F., & Angelier, J. 2001. Seismic attenuation and peak ground acceleration in Taiwan. *Bulletin of the Seismological Society of America*, **91**(5), 1229–1246.

Chapman, M. C. 1999. On the use of elastic input energy for seismic hazard analysis. *Earthquake Spectra*, **15**(4), 607–635.

Chen, Y., & Yu, Y.-X. 2008a. The development of attenuation relations in the rock sites for periods ($T = 0.04 \sim 10\,\mathrm{s}$, $\xi = 0.005$, 0.02, 0.07, 0.1 & 0.2) based on NGA database. *In: Proceedings of Fourteenth World Conference on Earthquake Engineering*. Paper no. 03-02-0029.

Chen, Y., & Yu, Y.-X. 2008b. The development of attenuation relations in the rock sites for periods ($T = 0.04 \sim 10\,\mathrm{s}$, $\xi = 0.05$) based on NGA database. *In: Proceedings of Fourteenth World Conference on Earthquake Engineering*. Paper no. 03-02-0017.

Chen, Y.-H., & Tsai, C.-C. P. 2002. A new method for estimation of the attenuation relationship with variance components. *Bulletin of the Seismological Society of America*, **92**(5), 1984–1991.

Chiaruttini, C., & Siro, L. 1981. The correlation of peak ground horizontal acceleration with magnitude, distance, and seismic intensity for Friuli and Ancona, Italy, and the Alpide belt. *Bulletin of the Seismological Society of America*, **71**(6), 1993–2009.

Chiou, B., Youngs, R., Abrahamson, N., & Addo, K. 2010. Ground-motion attenuation model for small-to-moderate shallow crustal earthquakes in California and its implications on regionalization of ground-motion prediction models. *Earthquake Spectra*, **26**(4), 907–926.

Chiou, B. S.-J., & Youngs, R. R. 2008. An NGA model for the average horizontal component of peak ground motion and response spectra. *Earthquake Spectra*, **24**(1), 173–215.

Choi, Y., & Stewart, J. P. 2005. Nonlinear site amplification as function of $30\,\mathrm{m}$ shear wave velocity. *Earthquake Spectra*, **21**(1), 1–30.

Chou, C.-C., & Uang, C.-M. 2000. Establishing absorbed energy spectra — an attenuation approach. *Earthquake Engineering and Structural Dynamics*, **29**(10), 1441–1455.

Chung, J.-K. 2006. Prediction of peak ground acceleration in southwestern Taiwan as revealed by analysis of CHY array data. *Terrestrial Atmospheric and Oceanic Science*, **17**(1), 139–167.

Climent, A., Taylor, W., Ciudad Real, M., Strauch, W., Villagrán, M., Dahle, A., & Bungum, H. 1994. *Spectral strong motion attenuation in Central America*. Tech. rept. 2-17. NORSAR.

Cole, S. W., Xu, Y., & Burton, P. W. 2008. Seismic hazard and risk in Shanghai and estimation of expected building damage. *Soil Dynamics and Earthquake Engineering*, **28**(10–11), 778–794.

Collins, N., Graves, R., Ichinose, G., & Somerville, P. 2006. *Ground motion attenuation relations for the Intermountain West*. Final report. U.S. Geological Survey. Award 05HQGR0031.

Cornell, C. A., Banon, H., & Shakal, A. F. 1979. Seismic motion and response prediction alternatives. *Earthquake Engineering and Structural Dynamics*, **7**(4), 295–315.

Costa, G., Suhadolc, P., & Panza, G. F. 1998. The Friuli (NE Italy) Accelerometric Network: Analysis of low-magnitude high-quality digital accelerometric data for seismological and engineering applications. *In: Proceedings of the Sixth U.S. National Conference on Earthquake Engineering*. Oakland, USA: Earthquake Engineering Research Institute. Seattle, USA. 31 May–4 June.

Costa, G., Suhadolc, P., Delise, A., Moratto, L., Furlanetto, E., & Fitzko, F. 2006. Estimation of site effects at some stations of the Friuli (NE Italy) accelerometric network (RAF). *Pages 729–739 of: Proceedings of Third International Symposium on the Effects of Surface Geology on Seismic Motion*, vol. 1. Paper number 089.

Cotton, F., Scherbaum, F., Bommer, J. J., & Bungum, H. 2006. Criteria for selecting and adjusting ground-motion models for specific target regions: Application to central Europe and rock sites. *Journal of Seismology*, **10**(2), 137–156.

Cotton, F., Pousse, G., Bonilla, F., & Scherbaum, F. 2008. On the discrepancy of recent European ground-motion observations and predictions from empirical models: Analysis of KiK-net accelerometric data and point-sources stochastic simulations. *Bulletin of the Seismological Society of America*, **98**(5), 2244–2261.

Cousins, W. J., Zhao, J. X., & Perrin, N. D. 1999. A model for the attenuation of peak ground acceleration in New Zealand earthquakes based on seismograph and accelerograph data. *Bulletin of the New Zealand Society for Earthquake Engineering*, **32**(4), 193–220.

Crouse, C. B. 1991. Ground-motion attenuation equations for earthquakes on the Cascadia subduction zones. *Earthquake Spectra*, **7**(2), 201–236.

Crouse, C. B., & McGuire, J. W. 1996. Site response studies for purpose of revising NEHRP seismic provisions. *Earthquake Spectra*, **12**(3), 407–439.

Crouse, C. B., Vyas, Y. K., & Schell, B. A. 1988. Ground motion from subduction-zone earthquakes. *Bulletin of the Seismological Society of America*, **78**(1), 1–25.

Cua, G., & Heaton, T. H. 2010. Characterizing average properties of southern California ground motion amplitudes and envelopes. *Bulletin of the Seismological Society of America*. Submitted.

Dahle, A., Bugum, H., & Kvamme, L. B. 1990a. Attenuation modelling based on intraplate earthquake recordings. *Pages 121–129 of: Proceedings of Ninth European Conference on Earthquake Engineering*, vol. 4-A.

Dahle, A., Bungum, H., & Kvamme, L. B. 1990b. Attenuation models inferred from intraplate earthquake recordings. *Earthquake Engineering and Structural Dynamics*, **19**(8), 1125–1141.

Dahle, A., Bungum, H., & Kvamme, L. B. 1991. Empirically derived PSV spectral attenuation models for intraplate conditions. *European Earthquake Engineering*, **3**, 42–52.

Dahle, A., Climent, A., Taylor, W., Bungum, H., Santos, P., Ciudad Real, M., Linholm, C., Strauch, W., & Segura, F. 1995. New spectral strong motion attenuation models for Central America. *Pages 1005–1012 of: Proceedings of the Fifth International Conference on Seismic Zonation*, vol. II.

Danciu, L., & Tselentis, G.-A. 2007a. Engineering ground-motion parameters attenuation relationships for Greece. *Bulletin of the Seismological Society of America*, **97**(1B), 162–183.

Danciu, L., & Tselentis, G.-A. 2007b (Apr). Engineering ground-motion parameters attenuation relationships for Greece. *Pages 327–334 of: Proceedings of the International Symposium on Seismic Risk Reduction: The JICA Technical Cooperation Project in Romania*. Paper ID 26.

Das, S., Gupta, I. D., & Gupta, V. K. 2002. A new attenuation model for north-east India. *Pages 151–158 of: Proceedings of the Twelfth Symposium of Earthquake Engineering, Roorkee, India*.

Davenport, A. J. 1972. *A statistical relationship between shock amplitude, magnitude, and epicentral distance and its appplication to seismic zoning*. Engineering Science Research Report BLWT-4-72. Western Ontario University. Not seen. Cited in Hays (1980).

De Natale, G., Faccioli, E., & Zollo, A. 1988. Scaling of peak ground motions from digital recordings of small earthquakes at Campi Flegrei, southern Italy. *Pure and Applied Geophysics*, **126**(1), 37–53.

Denham, D., & Small, G. R. 1971. Strong motion data centre: Bureau of mineral resources, Canada. *Bulletin of the New Zealand Society for Earthquake Engineering*, **4**(1), 15–30.

Denham, D., Small, G. R., & Everingham, I.B. 1973. Some strong-motion results from Papua New Guinea 1967–1972. *Pages 2324–2327 of: Proceedings of Fifth World Conference on Earthquake Engineering*, vol. 2.

Devillers, C., & Mohammadioun, B. 1981. French methodology for determining site-adapted SMS (Séisme Majoré de Sécurité) spectra. *In: Transactions of the 6th International Conference on Structural Mechanics in Reactor Technology*, vol. K(a). K 1/9.

Dhakal, Y. P., Takai, N., & Sasatani, T. 2008. Path effects on prediction equations of pseudo-velocity response spectra in northern Japan. *In: Proceedings of Fourteenth World Conference on Earthquake Engineering*. Paper no. 03-02-0023.

Donovan, N. C. 1973. A statistical evaluation of strong motion data including the February 9, 1971 San Fernando earthquake. *Pages 1252–1261 of: Proceedings of Fifth World Conference on Earthquake Engineering*, vol. 1.

Donovan, N. C., & Bornstein, A. E. 1978. Uncertainties in seismic risk analysis. *Journal of the Geotechnical Engineering Division, ASCE*, **104**(GT7), 869–887.

Douglas, J. 2001a (Jan). *A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates (1969 to 2000)*. ESEE Report 01-1. Department of Civil and Environmental Engineering, Imperial College, London.

Douglas, J. 2001b (Oct). *A critical reappraisal of some problems in engineering seismology*. Ph.D. thesis, University of London.

Douglas, J. 2002 (Oct). *Errata of and additions to ESEE Report No. 01-1: 'A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates (1969 to 2000)'*. Dept. report. Department of Civil and Environmental Engineering, Imperial College, London.

Douglas, J. 2003. Earthquake ground motion estimation using strong-motion records: A review of equations for the estimation of peak ground acceleration and response spectral ordinates. *Earth-Science Reviews*, **61**(1–2), 43–104.

Douglas, J. 2004a (Jan.). *Ground motion estimation equations 1964–2003: Reissue of ESEE Report No. 01-1: 'A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates (1969 to 2000)' with corrections and additions*. Tech. rept. 04-001-SM. Department of Civil and Environmental Engineering; Imperial College of Science, Technology and Medicine; London; U.K.

Douglas, J. 2004b. An investigation of analysis of variance as a tool for exploring regional differences in strong ground motions. *Journal of Seismology*, **8**(4), 485–496.

Douglas, J. 2006 (Dec). *Errata of and additions to 'Ground motion estimation equations 1964–2003'*. Intermediary report RP-54603-FR. BRGM, Orléans, France.

Douglas, J. 2007. On the regional dependence of earthquake response spectra. *ISET Journal of Earthquake Technology*, **44**(1), 71–99.

Douglas, J. 2008 (Dec). *Further errata of and additions to 'Ground motion estimation equations 1964–2003'*. Final report RP-56187-FR. BRGM, Orléans, France.

Douglas, J. 2010a. Assessing the epistemic uncertainty of ground-motion predictions. *In: Proceedings of the Ninth U.S. National and 10th Canadian Conference on Earthquake Engineering: Reaching Beyond Borders*. Paper no. 219.

Douglas, J. 2010b. Consistency of ground-motion predictions from the past four decades. *Bulletin of Earthquake Engineering*, **8**(6), 1515–1526.

Douglas, J., & Aochi, H. 2008. A survey of techniques for predicting earthquake ground motions for engineering purposes. *Surveys in Geophysics*, **29**(3), 187–220.

Douglas, J., & Boore, D. M. 2011. High-frequency filtering of strong-motion records. *Bulletin of Earthquake Engineering*, **9**(2), 395–409.

Douglas, J., & Halldórsson, H. 2010. On the use of aftershocks when deriving ground-motion prediction equations. *In: Proceedings of the Ninth U.S. National and 10th Canadian Conference on Earthquake Engineering: Reaching Beyond Borders*. Paper no. 220.

Douglas, J., & Smit, P. M. 2001. How accurate can strong ground motion attenuation relations be? *Bulletin of the Seismological Society of America*, **91**(6), 1917–1923.

Douglas, J., Bungum, H., & Scherbaum, F. 2006. Ground-motion prediction equations for southern Spain and southern Norway obtained using the composite model perspective. *Journal of Earthquake Engineering*, **10**(1), 33–72.

Dowrick, D. J., & Sritharan, S. 1993. Attenuation of peak ground accelerations in some recent New Zealand earthquakes. *Bulletin of the New Zealand National Society for Earthquake Engineering*, **26**(1), 3–13. Not seen. Reported in Stafford (2006).

Eberhart-Phillips, D., & McVerry, G. 2003. Estimating slab earthquake response spectra from a 3D Q model. *Bulletin of the Seismological Society of America*, **93**(6), 2649–2663.

El Hassan, Y. M. 1994. *Structural response to earthquake ground motion in Sudan*. M.Phil. thesis, University of Khartoum, Sudan. Not seen. Reported in Abdalla *et al.* (2001).

Electric Power Research Institute. 1988. *Engineering model of earthquake ground motion for eastern North America*. Final report NP-6074. Research project 2556-16. Investigators: McGuire, R. K., Toro, G. R., W. J. Silva.

Electric Power Research Institute. 1993a. Empirical ground motion data in eastern North America. *In:* Schneider, J. F. (ed), *Guidelines for determining design basis ground motions*, vol. EPRI TR-102293.

Electric Power Research Institute. 1993b. Engineering model of strong ground motions from earthquakes in the central and eastern United States. *In:* Schneider, J. F. (ed), *Guidelines for determining design basis ground motions*, vol. EPRI TR-102293.

Electric Power Research Institute. 2004 (Dec). *CEUS ground motion project final report*. Tech. rept. 1009684. EPRI, Palo Alto, CA, Dominion Energy, Glen Allen, VA, Entergy Nuclear, Jackson, MS, and Exelon Generation Company, Kennett Square, PA.

Espinosa, A. F. 1980. Attenuation of strong horizontal ground accelerations in the western United States and their relation to M_L. *Bulletin of the Seismological Society of America*, **70**(2), 583–616.

Esteva, L. 1970. Seismic risk and seismic design. *Pages 142–182 of:* Hansen, R.J. (ed), *Seismic Design for Nuclear Power Plants*. The M.I.T. Press.

Esteva, L. 1974. Geology and probability in the assessment of seismic risk. *In: Proceedings of the 2nd International Conference of the Association of Engineering Geology*. Not seen. Reported in Ambraseys (1978a).

Esteva, L., & Rosenblueth, E. 1964. Espectros de temblores a distancias moderadas y grandes. *Boletin Sociedad Mexicana de Ingenieria Sesmica*, **2**, 1–18. In Spanish.

Esteva, L., & Villaverde, R. 1973. Seismic risk, design spectra and structural reliability. *Pages 2586–2596 of: Proceedings of Fifth World Conference on Earthquake Engineering*, vol. 2.

Faccioli, E. 1978 (Jun). Response spectra for soft soil sites. *Pages 441–456 of: Proceedings of the ASCE Geotechnical Engineering Division Speciality Conference: Earthquake Engineering and Soil Dynamics*, vol. I.

Faccioli, E. 1979. Engineering seismic risk analysis of the Friuli region. *Bollettino di Geofisica Teorica ed Applicata*, **XXI**(83), 173–190.

Faccioli, E., & Agalbato, D. 1979. Attenuation of strong-motion parameters in the 1976 Friuli, Italy, earthquakes. *Pages 233–242 of: Proceedings of the Second U.S. National Conference on Earthquake Engineering*.

Faccioli, E., Bianchini, A., & Villani, M. 2010 (Mar). New ground motion prediction equations for $T > 1\,\mathrm{s}$ and their influence on seismic hazard assessment. *In: Proceedings of the University of Tokyo Symposium on Long-Period Ground Motion and Urban Disaster Mitigation*.

Fajfar, P., & Peruš, I. 1997. A non-parametric approach to attenuation relations. *Journal of Earthquake Engineering*, **1**(2), 319–340.

Field, E. H. 2000. A modified ground-motion attenuation relationship for southern California that accounts for detailed site classification and a basin-depth effect. *Bulletin of the Seismological Society of America*, **90**(6B), S209–S221.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E. V., Dickman, N., Hanson, S., & Hopper, M. 1996. *National Seismic-Hazard Maps: Documentation June 1996*. Open-File Report 96-532. U.S. Department of the Interior, U.S. Geological Survey.

Free, M. W. 1996. *The attenuation of earthquake strong-motion in intraplate regions*. Ph.D. thesis, University of London.

Free, M. W., Ambraseys, N. N., & Sarma, S. K. 1998 (Feb). *Earthquake ground-motion attenuation relations for stable continental intraplate regions*. ESEE Report 98-1. Department of Civil Engineering, Imperial College, London.

Frisenda, M., Massa, M., Spallarossa, D., Ferretti, G., & Eva, C. 2005. Attenuation relationships for low magnitude earthquakes using standard seismometric records. *Journal of Earthquake Engineering*, **9**(1), 23–40.

Frohlich, C., & Apperson, K. D. 1992. Earthquake focal mechanisms, moment tensors, and the consistency of seismic activity near plate boundaries. *Tectonics*, **11**(2), 279–296.

Fukushima, Y., & Tanaka, T. 1990. A new attenuation relation for peak horizontal acceleration of strong earthquake ground motion in Japan. *Bulletin of the Seismological Society of America*, **80**(4), 757–783.

Fukushima, Y., Tanaka, T., & Kataoka, S. 1988. A new attenuation relationship for peak ground acceleration derived from strong-motion accelerograms. *Pages 343–348 of: Proceedings of Ninth World Conference on Earthquake Engineering*, vol. II.

Fukushima, Y., Gariel, J.-C., & Tanaka, R. 1994. Prediction relations of seismic motion parameters at depth using borehole data. *Pages 417–422 of: Proceedings of Tenth European Conference on Earthquake Engineering*, vol. 1.

Fukushima, Y., Gariel, J.-C., & Tanaka, R. 1995. Site-dependent attenuation relations of seismic motion parameters at depth using borehole data. *Bulletin of the Seismological Society of America*, **85**(6), 1790–1804.

Fukushima, Y., Berge-Thierry, C., Volant, P., Griot-Pommera, D.-A., & Cotton, F. 2003. Attenuation relation for western Eurasia determined with recent near-fault records from California, Japan and Turkey. *Journal of Earthquake Engineering*, **7**(4), 573–598.

Fukushima, Y., Zhao, J. X., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Fukushima, Y., Thio, H. K., & Somerville, P. G. 2006. Attenuation relations of strong ground motion in Japan using site classification based on predominant period. *In: Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*. Paper number 683.

Fukushima, Y., Bonilla, F., Scotti, O., & Douglas, J. 2007a (Jul). Impact of site classification on deriving empirical ground-motion prediction equations: Application to the west Eurasia dataset. *In: 7ème Colloque National AFPS 2007*.

Fukushima, Y., Bonilla, L. F., Scotti, O., & Douglas, J. 2007b. Site classification using horizontal-to-vertical response spectral ratios and its impact when deriving empirical ground motion prediction equations. *Journal of Earthquake Engineering*, **11**(5), 712–724.

García, D., Singh, S. K., Herráiz, M., Ordaz, M., & Pacheco, J. F. 2005. Inslab earthquakes of central Mexico: Peak ground-motion parameters and response spectra. *Bulletin of the Seismological Society of America*, **95**(6), 2272–2282.

Garcia, S., & Romo, M. 2006 (Sep). Machine learning for ground-motion relations. *In: Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*. Paper no. 1438.

Garcìa-Fernàndez, M., & Canas, J. A. 1991. Estimation of regional values of peak ground acceleration from short-period seismograms. *Pages 533–539 of: Proceedings of the Fourth International Conference on Seismic Zonation*, vol. II.

Garcia-Fernandez, M., & Canas, J.A. 1992. Regional Lg-wave attenuation and estimates of peak ground acceleration in the Iberian peninsula. *Pages 439–443 of: Proceedings of Tenth World Conference on Earthquake Engineering*, vol. 1.

Garcia-Fernandez, M., & Canas, J.A. 1995. Regional peak ground acceleration estimates in the Iberian peninsula. *Pages 1029–1034 of: Proceedings of the Fifth International Conference on Seismic Zonation*, vol. II.

Gaull, B. A. 1988. Attenuation of strong ground motion in space and time in southwest Western Australia. *Pages 361–366 of: Proceedings of Ninth World Conference on Earthquake Engineering*, vol. II.

Geomatrix Consultants. 1991 (Mar). *Seismic ground motion study for West San Francisco Bay Bridge*. Report for caltrans, division of structures, sacramento, california. Not seen. Cited in Idriss (1993).

Ghasemi, H., Zare, M., Fukushima, Y., & Koketsu, K. 2009. An empirical spectral ground-motion model for Iran. *Journal of Seismology*, **13**(4), 499–515.

Ghodrati Amiri, G., Mahdavian, A., & Dana, F. M. 2007a. Attenuation relationships for Iran. *Journal of Earthquake Engineering*, **11**(4), 469Ű–492.

Ghodrati Amiri, G., Mahdavian, A., & Dana, F. M. 2007b. Response on the Discussion of ‘Attenuation relationships for Iran’. *Journal of Earthquake Engineering*, **11**(6), 1036Ű–1037.

Ghodrati Amiri, G., Khorasani, M., Mirza Hessabi, M., & Razavian Amrei, S. A. 2010. Ground-motion prediction equations of spectral ordinates and Arias intensity for Iran. *Journal of Earthquake Engineering*, **14**(1), 1–29.

Gitterman, Y., Zaslavsky, Y., & Shapira, A. 1993 (Sep). Analysis of strong records in Israel. *In: Proceedings of XVIIth regional European seminar on earthquake engineering, Haifa, Israel*. Not seen.

Goda, K., & Hong, H. P. 2008. Spatial correlation of peak ground motions and response spectra. *Bulletin of the Seismological Society of America*, **98**(1), 354–365.

Gómez-Soberón, C., Tena-Colunga, A., & Ordaz, M. 2006 (Apr). Updated attenuation laws in displacement and acceleration for the Mexican Pacific coast as the first step to improve current design spectra for base-isolated structures in Mexico. *In: Proceedings of the Eighth U.S. National Conference on Earthquake Engineering*. Paper no. 1010.

Graizer, V., & Kalkan, E. 2007. Ground motion attenuation model for peak horizontal acceleration from shallow crustal earthquakes. *Earthquake Spectra*, **23**(3), 585–613.

Graizer, V., & Kalkan, E. 2008. A novel approach to strong ground motion attenuation modeling. *In: Proceedings of Fourteenth World Conference on Earthquake Engineering*. Paper no. 02-0022.

Graizer, V., Kalkan, E., & Lin, K.-W. 2010. Extending and testing Graizer-Kalkan ground motion attenuation model based on Atlas database of shallow crustal events. *In: Proceedings of the Ninth U.S. National and 10th Canadian Conference on Earthquake Engineering: Reaching Beyond Borders*. Paper no. 568.

Gregor, N., Silva, W., & Darragh, B. 2002a (Jun.). *Development of attenuation relations for peak particle velocity and displacement*. A pearl report to pg&e/cec/caltrans. Pacific Engineering and Analysis, El Cerrito, U.S.A.

Gregor, N. J., Silva, W. J., Wong, I. G., & Youngs, R. R. 2002b. Ground-motion attenuation relationships for Cascadia subduction zone megathrust earthquakes based on a stochastic finite-fault model. *Bulletin of the Seismological Society of America*, **92**(5), 1923–1932.

Gülkan, P., & Kalkan, E. 2002. Attenuation modeling of recent earthquakes in Turkey. *Journal of Seismology*, **6**(3), 397–409.

Güllü, H., & Erçelebi, E. 2007. A neural network approach for attenuation relationships: An application using strong ground motion data from Turkey. *Engineering Geology*, **93**(3–4), 65–81.

Günaydın, K., & Günaydın, A. 2008. Peak ground acceleration prediction by artifical neural networks for northwestern Turkey. *Mathematical Problems in Engineering*. Article ID 919420.

Gupta, I. D. 2010. Response spectral attenuation relations for in-slab earthquakes in Indo-Burmese subduction zone. *Soil Dynamics and Earthquake Engineering*, **30**(5), 368–377.

Gupta, S., & Gupta, I. D. 2004. The prediction of earthquake peak ground acceleration in Koyna region, India. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 1437.

Gusev, A. A., Gordeev, E. I., Guseva, E. M., Petukhin, A. G., & Chebrov, V. N. 1997. The first version of the $A_{max}(m_w, r)$ relationship for Kamchatka. *Pure and Applied Geophysics*, **149**(2), 299–312.

Halldorsson, B., & Papageorgiou, A. S. 2005. Calibration of the specific barrier model to earthquakes of different tectonic regions. *Bulletin of the Seismological Society of America*, **95**(4), 1276–1300.

Halldórsson, P., & Sveinsson, B. I. 2003 (Aug). *Dvínun hröðunar á Íslandi*. Tech. rept. 03025. Veðurstofa Íslands (Icelandic Meteorological Office).

Hamzehloo, H., & Bahoosh, H. R. 2010. Theoretical spectral attenuation relationship for Tehran region, Iran. *In: Proceedings of Fourteenth European Conference on Earthquake Engineering*. Paper no. 821.

Hancock, J., & Bommer, J. J. 2005. The effective number of cycles of earthquake ground motion. *Earthquake Engineering and Structural Dynamics*, **34**, 637–664.

Hao, H., & Gaull, B. A. 2009. Estimation of strong seismic ground motion for engineering use in Perth Western Australia. *Soil Dynamics and Earthquake Engineering*, **29**(5), 909–924.

Hasegawa, H. S., Basham, P. W., & Berry, M. J. 1981. Attenuation relations for strong seismic ground motion in Canada. *Bulletin of the Seismological Society of America*, **71**(6), 1943–1962.

Hays, W. W. 1980. *Procedures for estimating earthquake ground motions*. Geological Survey Professional Paper 1114. US Geological Survey.

Herak, M., Markušić, S., & Ivančić, I. 2001. Attenuation of peak horizontal and vertical acceleration in the Dinarides area. *Studia Geophysica et Geodaetica*, **45**(4), 383–394.

Hernandez, B., Fukushima, Y., Bossu, R., & Albaric, J. 2006. Seismic attenuation relation for Hualien (Taiwan) at the free surface and down to $52.6\,\mathrm{m}$ deep. *Pages 145–154 of: Proceedings of Third International Symposium on the Effects of Surface Geology on Seismic Motion*, vol. 1. Paper number 008.

Herrmann, R. B., & Goertz, M. J. 1981. A numerical study of peak ground motion scaling. *Bulletin of the Seismological Society of America*, **71**(6), 1963–1979.

Herrmann, R. B., & Nuttli, O. W. 1984. Scaling and attenuation relations for strong ground motion in eastern North America. *Pages 305–309 of: Proceedings of Eighth World Conference on Earthquake Engineering*, vol. II.

Hong, H. P., & Goda, K. 2007. Orientation-dependent ground-motion measure for seismic-hazard assessment. *Bulletin of the Seismological Society of America*, **97**(5), 1525–1538.

Hong, H. P., & Goda, K. 2010. Characteristics of horizontal ground motion measures along principal directions. *Earthquake Engineering and Engineering Vibration*, **9**(1), 9–22.

Hong, H. P., Zhang, Y., & Goda, K. 2009a. Effect of spatial correlation on estimated ground-motion prediction equations. *Bulletin of the Seismological Society of America*, **99**(2A), 928–934.

Hong, H. P., Pozos-Estrada, A., & Gomez, R. 2009b. Orientation effect on ground motion measurements for Mexican subduction earthquakes. *Earthquake Engineering and Engineering Vibration*, **8**(1), 1–16.

Humbert, N., & Viallet, E. 2008. An evaluation of epistemic and random uncertainties included in attenuation relationship parameters. *In: Proceedings of Fourteenth World Conference on Earthquake Engineering*. Paper no. 07-0117.

Huo, J., & Hu, Y. 1991. Attenuation laws considering the randomness of magnitude and distance. *Earthquake Research in China*, **5**(1), 17–36.

Huo, J., Hu, Y., & Feng, Q. 1992. Study on estimation of ground motion from seismic intensity. *Earthquake Engineering and Engineering Vibration*, **12**(3), 1–15. In Chinese. Not seen.

Hwang, H., & Huo, J.-R. 1997. Attenuation relations of ground motion for rock and soil sites in eastern United States. *Soil Dynamics and Earthquake Engineering*, **16**(6), 363–372.

Idriss, I. M. 1978 (Jun). Characteristics of earthquake ground motions. *Pages 1151–1265 of: Proceedings of the ASCE Geotechnical Engineering Division Speciality Conference: Earthquake Engineering and Soil Dynamics*, vol. III.

Idriss, I. M. 1993. *Procedures for selecting earthquake ground motions at rock sites*. Tech. rept. NIST GCR 93-625. National Institute of Standards and Technology.

Idriss, I. M. 2008. An NGA empirical model for estimating the horizontal spectral values generated by shallow crustal earthquakes. *Earthquake Spectra*, **24**(1), 217–242.

Inan, E., Colakoglu, Z., Koc, N., Bayülke, N., & Coruh, E. 1996. *Earthquake catalogs with acceleration records from 1976 to 1996*. Tech. rept. General Directorate of Disaster Affairs, Earthquake Research Department, Ankara, Turkey. In Turkish. Not seen. Reported in Ulusay *et al.* (2004).

Iwasaki, T., Kawashima, K., & Saeki, M. 1980. Effects of seismic and geotechnical conditions on maximum ground accelerations and response spectra. *Pages 183–190 of: Proceedings of Seventh World Conference on Earthquake Engineering*, vol. 2.

Iyengar, R. N., & Raghu Kanth, S. T. G. 2004. Attenuation of strong ground motion in peninsular India. *Seismological Research Letters*, **75**(4), 530–540.

Jacob, K. H., Gariel, J.-C., Armbruster, J., Hough, S., Friberg, P., & Tuttle, M. 1990 (May). Site-specific ground motion estimates for New York City. *Pages 587–596 of: Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*, vol. 1.

Jain, S. K., Roshan, A. D., Arlekar, J. N., & Basu, P. C. 2000 (Nov). Empirical attenuation relationships for the Himalayan earthquakes based on Indian strong motion data. *In: Proceedings of the Sixth International Conference on Seismic Zonation*.

Jara-Guerrero, J. M., Jara-Diaz, M., & Hernández, H. 2007 (Apr). Estimation of the pseudoacceleration response spectra in sites of Mexico. *Pages 343–350 of: Proceedings of the International Symposium on Seismic Risk Reduction: The JICA Technical Cooperation Project in Romania*. Paper ID 13.

Jayaram, N., & Baker, J. W. 2010. Considering spatial correlation in mixed-effects regression and the impact on ground-motion models. *Bulletin of the Seismological Society of America*, **100**(6), 3295–3303.

Jeon, Y.-S., & Herrmann, R. B. 2004. High-frequency earthquake ground-motion scaling in Utah and Yellowstone. *Bulletin of the Seismological Society of America*, **94**(5), 1644–1657.

Jin, X., Kang, L.-C., & Ou, Y.-P. 2008. Ground motion attenuation relation for small to moderate earthquakes in Fujian region, China. *Acta Seismologica Sinica*, **21**(3), 283–295.

Johnson, R. A. 1973. An earthquake spectrum prediction technique. *Bulletin of the Seismological Society of America*, **63**(4), 1255–1274.

Johnston, A., *et al.* . 1994. *The earthquakes of stable continental regions, Vol. 1: Assessment of large earthquake potential*. EPRI Report TR-102261. Electrical Power Research Institute, Palo Alto.

Joyner, W. B., & Boore, D. M. 1981. Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake. *Bulletin of the Seismological Society of America*, **71**(6), 2011–2038.

Joyner, W. B., & Boore, D. M. 1982a. *Estimation of response-spectral values as functions of magnitude, distance, and site conditions*. Open-File Report 82-881. U.S. Geological Survey.

Joyner, W. B., & Boore, D. M. 1982b. *Prediction of earthquake response spectra*. Open-File Report 82-977. U.S. Geological Survey.

Joyner, W. B., & Boore, D. M. 1988. Measurement, characterization, and prediction of strong ground motion. *Pages 43–102 of: Proceedings of Earthquake Engineering & Soil Dynamics II*. Geotechnical Division, ASCE.

Joyner, W. B., & Boore, D. M. 1993. Methods for regression analysis of strong-motion data. *Bulletin of the Seismological Society of America*, **83**(2), 469–487.

Joyner, W. B., & Boore, D. M. 1996 (Aug). Recent developments in strong motion attenuation relationships. *Pages 101–116 of: Proceedings of the 28th Joint Meeting of the U.S.-Japan Cooperative Program in Natural Resource Panel on Wind and Seismic Effects*.

Joyner, W. B., & Fumal, T. E. 1984. Use of measured shear-wave velocity for predicting geologic site effects on strong ground motion. *Pages 777–783 of: Proceedings of Eighth World Conference on Earthquake Engineering*, vol. II.

Joyner, W. B., & Fumal, T. E. 1985. Predictive mapping of earthquake ground motion. *Pages 203–220 of: Evaluating Earthquake Hazards in the Los Angeles Region — An Earth Science Perspective*. U.S. Geological Survey Professional Paper, no. 1360. Washington: United States Government Printing Office.

Junn, J.-G., Jo, N.-D., & Baag, C.-E. 2002. Stochastic prediction of ground motions in southern Korea. *Geosciences Journal*, **6**(3), 203–214.

Kalkan, E., & Gülkan, P. 2004a. Empirical attenuation equations for vertical ground motion in Turkey. *Earthquake Spectra*, **20**(3), 853–882.

Kalkan, E., & Gülkan, P. 2004b. Site-dependent spectra derived from ground motion records in Turkey. *Earthquake Spectra*, **20**(4), 1111–1138.

Kalkan, E., & Gülkan, P. 2005. Erratum: Site-dependent spectra derived from ground motion records in Turkey. *Earthquake Spectra*, **21**(1), 283.

Kamiyama, M. 1989 (Oct). Regression analyses of strong-motion spectra in terms of a simplified faulting source model. *Pages 113–126 of: Proceedings of the Fourth International Conference on Soil Dynamics and Earthquake Engineering*.

Kamiyama, M. 1995. An attenuation model for the peak values of strong ground motions with emphasis on local soil effects. *Pages 579–585 of: Proceedings of the First International Conference on Earthquake Geotechnical Engineering*, vol. 1.

Kamiyama, M., & Yanagisawa, E. 1986. A statisical model for estimating response spectra of strong earthquake ground motions with emphasis on local soil conditions. *Soils and Foundations*, **26**(2), 16–32.

Kamiyama, M., O'Rourke, M.J., & Flores-Berrones, R. 1992 (Sep). *A semi-empirical analysis of strong-motion peaks in terms of seismic source, propagation path and local site conditions*. Tech. rept. NCEER-92-0023. National Center for Earthquake Engineering Research.

Kanai, K. 1966. Improved empirical formula for characteristics of stray [sic] earthquake motions. *Pages 1–4 of: Proceedings of the Japanese Earthquake Symposium*. Not seen. Reported in Trifunac & Brady (1975).

Kang, L., & Jin, X. 2009. Ground motion attenuation relations of small and moderate earthquakes in Sichuan region. *Earthquake Science*, **22**, 277–282.

Kanno, T., Narita, A., Morikawa, N., Fujiwara, H., & Fukushima, Y. 2006. A new attenuation relation for strong ground motion in Japan based on recorded data. *Bulletin of the Seismological Society of America*, **96**(3), 879–897.

Katayama, T. 1982. An engineering prediction model of acceleration response spectra and its application to seismic hazard mapping. *Earthquake Engineering and Structural Dynamics*, **10**(1), 149–163.

Kawano, H., Takahashi, K., Takemura, M., Tohdo, M., Watanabe, T., & Noda, S. 2000. Empirical response spectral attenuations on the rocks with $\mathrm{VS} = 0.5$ to $3.0\,\mathrm{km/s}$ in Japan. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper No. 0953.

Kawashima, K., Aizawa, K., & Takahashi, K. 1984. Attenuation of peak ground motion and absolute acceleration response spectra. *Pages 257–264 of: Proceedings of Eighth World Conference on Earthquake Engineering*, vol. II.

Kawashima, K., Aizawa, K., & Takahashi, K. 1985. Attenuation of peak ground motions and absolute acceleration response spectra of vertical earthquake ground motion. *Proceedings of JSCE Structural Engineering/Earthquake Engineering*, **2**(2), 415–422.

Kawashima, K., Aizawa, K., & Takahashi, K. 1986. Attenuation of peak ground acceleration, velocity and displacement based on multiple regression analysis of Japanese strong motion records. *Earthquake Engineering and Structural Dynamics*, **14**(2), 199–215.

Khademi, M. H. 2002 (Sep). Attenuation of peak and spectral accelerations in the Persian plateau. *In: Proceedings of Twelfth European Conference on Earthquake Engineering*. Paper reference 330.

Kobayashi, H., & Midorikawa, S. 1982. A semi-empirical method for estimating response spectra of near-field ground motions with regard to fault rupture. *Pages 161–168 of: Proceedings of Seventh European Conference on Earthquake Engineering*, vol. 2.

Kobayashi, H., & Nagahashi, S. 1977. Response spectra on seismic bedrock during earthquake. *Pages 516–522 of: Proceedings of Sixth World Conference on Earthquake Engineering*, vol. I.

Kobayashi, S., Takahashi, T., Matsuzaki, S., Mori, M., Fukushima, Y., Zhao, J. X., & Somerville, P. G. 2000. A spectral attenuation model for Japan using digital strong motion records of JMA87 type. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper No. 2786.

Krinitzsky, E. L., Chang, F. K., & Nuttli, O. W. 1987 (Sep). *State-of-the-art for assessing earthquake hazards in the United States; report 26, Parameters for specifying magnitude-related earthquake ground motions*. Tech. rept. U.S. Army Engineer Waterways Experimental Station. Miscellaneous paper S-73-1.

Krinitzsky, E. L., Chang, F. K., & Nuttli, O. W. 1988. Magnitude-related earthquake ground motions. *Bulletin of the Association of Engineering Geologists*, **XXV**(4), 399–423.

Kuehn, N. M., Scherbaum, F., & Riggelsen, C. 2009. Deriving empirical ground-motion models: Balancing data constraints and physical assumptions to optimize prediction capability. *Bulletin of the Seismological Society of America*, **99**(4), 2335–2347.

Laouami, N., Slimani, A., Bouhadad, Y., Chatelain, J.-L., & Nour, A. 2006. Evidence for fault-related directionality and localized site effects from strong motion recordings of the 2003 Boumerdes (Algeria) earthquake: Consequences on damage distribution and the Algerian seismic code. *Soil Dynamics and Earthquake Engineering*, **26**(11), 991–1003.

Lawson, R. S., & Krawinkler, H. 1994. Cumulative damage potential of seismic ground motion. *Pages 1079–1086 of: Proceedings of Tenth European Conference on Earthquake Engineering*, vol. 2.

Lee, V. W. 1987 (Jul). *Influence of local soil and geological site conditions on pseudo relative velocity spectrum amplitudes of recorded strong motion accelerations*. Tech. rept. CE 87-06. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

Lee, V. W. 1993. Scaling PSV from earthquake magnitude, local soil, and geologic depth of sediments. *Journal of the Geotechnical Engineering Division, ASCE*, **119**(1), 108–126.

Lee, V. W. 1995. Pseudo relative velocity spectra in former Yugoslavia. *European Earthquake Engineering*, **IX**(1), 12–22.

Lee, V. W., & Manić, M. 1994. Empirical scaling of response spectra in former Yugoslavia. *Pages 2567–2572 of: Proceedings of Tenth European Conference on Earthquake Engineering*, vol. 4.

Lee, V. W., & Trifunac, M. D. 1995 (May). *Pseudo relative velocity spectra of strong earthquake ground motion in California*. Tech. rept. CE 95-04. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

Lee, V. W., Trifunac, M. D., Todorovska, M. I., & Novikova, E. I. 1995 (Apr). *Empirical equations describing attenuation of peak of strong ground motion, in terms of magnitude, distance, path effects and site conditions*. Tech. rept. CE 95-02. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

Liang, J., Hao, H., Gaull, B. A., & Sinadinovski, C. 2008. Estimation of strong ground motions in southwest Western Australia with a combined Green's function and stochastic approach. *Journal of Earthquake Engineering*, **12**(3), 382–405.

Lin, P.-S., & Lee, C.-T. 2008. Ground-motion attenuation relationships for subduction-zone earthquakes in northeastern Taiwan. *Bulletin of the Seismological Society of America*, **98**(1), 220–240.

Liu, K.-S., & Tsai, Y.-B. 2005. Attenuation relationships of peak ground acceleration and velocity for crustal earthquakes in Taiwan. *Bulletin of the Seismological Society of America*, **95**(3), 1045–1058.

Loh, C.-H., Yeh, Y. T., Jean, W.-Y., & Yeh, Y.-H. 1991. Probabilistic seismic risk analysis in the Taiwan area based on PGA and spectral amplitude attenuation formulas. *Engineering Geology*, **30**(3–4), 277–304.

Lubkowski, Z., Bommer, J., Baptie, B., Bird, J., Douglas, J., Free, M., Hancock, J., Sargeant, S., Sartain, N., & Strasser, F. 2004. An evaluation of attenuation relationships for seismic hazard assessment in the UK. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 1422.

Lungu, D., Demetriu, S., Radu, C., & Coman, O. 1994. Uniform hazard response spectra for Vrancea earthquakes in Romania. *Pages 365–370 of: Proceedings of Tenth European Conference on Earthquake Engineering*, vol. 1.

Lungu, D., Coman, O., & Moldoveanu, T. 1995a (Aug). Hazard analysis for Vrancea earthquakes. Application to Cernavoda NPP site in Romania. *In: Proceedings of the 13th International Conference on Structural Mechanics in Reactor Technology*. Division K, Paper No. 538.

Lungu, D., Cornea, T., Craifaleanu, I., & Aldea, A. 1995b. Seismic zonation of Romania based on uniform hazard response ordinates. *Pages 445–452 of: Proceedings of the Fifth International Conference on Seismic Zonation*, vol. I.

Lungu, D., Cornea, T., Craifaleanu, I., & Demetriu, S. 1996 (Jun). Probabilistic seismic hazard analysis for inelastic structures on soft soils. *In: Proceedings of Eleventh World Conference on Earthquake Engineering*.

Lussou, P., Bard, P. Y., Cotton, F., & Fukushima, Y. 2001. Seismic design regulation codes: Contribution of K-Net data to site effect evaluation. *Journal of Earthquake Engineering*, **5**(1), 13–33.

Luzi, L., Morasca, P., Zolezzi, F., Bindi, D., Pacor, F., Spallarossa, D., & Franceschina, G. 2006. Ground motion models for Molise region (southern Italy). *In: Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*. Paper number 938.

Lyubushin, A. A., & Parvez, I. A. 2010. Map of seismic hazard of India using Bayesian approach. *Natural Hazards*, **55**(2), 543–556.

Mahdavian, A. 2006. Empirical evaluation of attenuation relations of peak ground acceleration in the Zagros and central Iran. *In: Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*. Paper number 558.

Malagnini, L., & Herrmann, R. B. 2000. Ground-motion scaling in the region of the 1997 Umbria-Marche earthquake (Italy). *Bulletin of the Seismological Society of America*, **90**(4), 1041–1051.

Malagnini, L., Herrmann, R. B., & Di Bona, M. 2000a. Ground-motion scaling in the Apennines (Italy). *Bulletin of the Seismological Society of America*, **90**(4), 1062–1081.

Malagnini, L., Herrmann, R. B., & Koch, K. 2000b. Regional ground-motion scaling in central Europe. *Bulletin of the Seismological Society of America*, **90**(4), 1052–1061.

Malagnini, L., Akinci, A., Herrmann, R. B., Pino, N. A., & Scognamiglio, L. 2002. Characteristics of the ground motion in northeastern Italy. *Bulletin of the Seismological Society of America*, **92**(6), 2186–2204.

Malagnini, L., Mayeda, K., Uhrhammer, R., Akinci, A., & Herrmann, R. B. 2007. A regional ground-motion excitation/attenuation model for the San Francisco region. *Bulletin of the Seismological Society of America*, **97**(3), 843–862.

Malkawi, A. I. H., & Fahmi, K. J. 1996. Locally derived earthquake ground motion attenuation relations for Jordan and conterminous areas. *Quarterly Journal of Engineering Geology and Hydrogeology*, **29**(4), 309–319.

Mandal, P., Kumar, N., Satyamurthy, C., & Raju, I. P. 2009. Ground-motion attenuation relation from strong-motion records of the 2001 Mw 7.7 Bhuj earthquake sequence (2001–2006), Gujarat, India. *Pure and Applied Geophysics*, **166**(3), 451–469.

Manic, M. I. 1998. A new site dependent attenuation model for prediction of peak horizontal acceleration in Northwestern Balkan. *In: Proceedings of Eleventh European Conference on Earthquake Engineering*.

Manic, M. I. 2002 (Sep). Empirical scaling of response spectra for the territory of north-western Balkan. *In: Proceedings of Twelfth European Conference on Earthquake Engineering*. Paper reference 650.

Margaris, B., Papazachos, C., Papaioannou, C., Theodulidis, N., Kalogeras, I., & Skarlatoudis, A. 2002a (Sep). Ground motion attenuation relations for shallow earthquakes in Greece. *In: Proceedings of the XXVIII General Assembly of the European Seismological Commission (ESC)*.

Margaris, B., Papazachos, C., Papaioannou, C., Theodulidis, N., Kalogeras, I., & Skarlatoudis, A. 2002b (Sep). Ground motion attenuation relations for shallow earthquakes in Greece. *In: Proceedings of Twelfth European Conference on Earthquake Engineering*. Paper reference 385.

Marin, S., Avouac, J.-P., Nicolas, M., & Schlupp, A. 2004. A probabilistic approach to seismic hazard in metropolitan France. *Bulletin of the Seismological Society of America*, **94**(6), 2137–2163.

Massa, M., Marzorati, S., D'Alema, E., Di Giacomo, D., & Augliera, P. 2007. Site classification assessment for estimating empirical attenuation relationships for central-northern Italy earthquakes. *Journal of Earthquake Engineering*, **11**(6), 943Ű–967.

Massa, M., Morasca, P., Moratto, L., Marzorati, S., Costa, G., & Spallarossa, D. 2008. Empirical ground-motion prediction equations for northern Italy using weak- and strong-motion amplitudes, frequency content, and duration parameters. *Bulletin of the Seismological Society of America*, **98**(3), 1319–1342.

Matsumoto, N., Sasaki, T., Inagaki, K., & Annaka, T. 2004. Attenuation relations of acceleration response spectra at dam foundations in Japan. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 689.

Matuschka, T. 1980. *Assessment of seismic hazards in New Zealand*. Tech. rept. 222. Department of Civil Engineering, School of Engineering, University of Auckland. Not seen. Reported in Stafford (2006).

Matuschka, T., & Davis, B. K. 1991. Derivation of an attenuation model in terms of spectral acceleration for New Zealand. *In: Pacific conference on earthquake engineering*. Not seen. Reported in Stafford (2006).

McCann Jr., M. W., & Echezwia, H. 1984. Investigating the uncertainty in ground motion prediction. *Pages 297–304 of: Proceedings of Eighth World Conference on Earthquake Engineering*, vol. II.

McCue, K. 1986. Strong motion attenuation in eastern Australia. *In: Earthquake Engineering Symposium*. National Conference Publication 86/15. Institution of Engineers Australia. Not seen. Reported in Free (1996).

McCue, K., Gibson, G., & Wesson, V. 1988. Intraplate recording of strong motion in southeastern Australia. *Pages 355–360 of: Proceedings of Ninth World Conference on Earthquake Engineering*, vol. II.

McGarr, A., & Fletcher, J. B. 2005. Development of ground-motion prediction equations relevant to shallow mining-induced seismicity in the Trail Mountain area, Emery County, Utah. *Bulletin of the Seismological Society of America*, **95**(1), 31–47.

McGuire, R. K. 1974. *Seismic structural response risk analysis, incorporating peak response regressions on earthquake magnitude and distance*. Research Report R74-51. Massachusetts Institute of Technology, Department of Civil Engineering, Cambridge, USA. Not seen.

McGuire, R. K. 1976. *FORTRAN computer program for seismic risk analysis*. Open-File Report 76-67. United States Department of the Interior Geological Survey.

McGuire, R. K. 1977. Seismic design spectra and mapping procedures using hazard analysis based directly on oscillator response. *Earthquake Engineering and Structural Dynamics*, **5**, 211–234.

McGuire, R. K. 1978. Seismic ground motion parameter relations. *Journal of the Geotechnical Engineering Division, ASCE*, **104**(GT4), 481–490.

McVerry, G. H., Dowrick, D. J., Sritharan, S., Cousins, W. J., & Porritt, T. E. 1993. Attenuation of peak ground accelerations in New Zealand. *Pages 23–38 of: Proceedings of the International Workshop on Strong Motion Data*, vol. 2. Not seen. Cited in McVerry *et al.* (1995).

McVerry, G. H., Dowrick, D. J., & Zhao, J. X. 1995 (November). Attenuation of peak ground accelerations in New Zealand. *Pages 287–292 of: Pacific Conference on Earthquake Engineering*, vol. 3.

McVerry, G. H., Zhao, J. X., Abrahamson, N. A., & Somerville, P. G. 2000. Crustal and subduction zone attenuation relations for New Zealand earthquakes. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper No. 1834.

McVerry, G. H., Zhao, J. X., Abrahamson, N. A., & Somerville, P. G. 2006. New Zealand acceleration response spectrum attenuation relations for crustal and subduction zone earthquakes. *Bulletin of the New Zealand Society for Earthquake Engineering*, **39**(4), 1–58.

Megawati, K. 2007. Hybrid simulations of ground motions from local earthquakes affecting Hong Kong. *Bulletin of the Seismological Society of America*, **97**(4), 1293–1307.

Megawati, K., & Pan, T.-C. 2010. Ground-motion attenuation relationship for the Sumatran megathrust earthquakes. *Earthquake Engineering and Structural Dynamics*, **39**, 827–845.

Megawati, K., Pan, T.-C., & Koketsu, K. 2003. Response spectral attenuation relationships for Singapore and the Malay peninsula due to distant Sumatran-fault earthquakes. *Earthquake Engineering and Structural Dynamics*, **32**(14), 2241–2265.

Megawati, K., Pan, T.-C., & Koketsu, K. 2005. Response spectral attenuation relationships for Sumatran-subduction earthquakes and the seismic hazard implications to Singapore and Kuala Lumpur. *Soil Dynamics and Earthquake Engineering*, **25**(1), 11–25.

Meirova, T., Hofstetter, R., Ben-Avraham, Z., Steinberg, D. M., Malagnini, L., & Akinci, A. 2008. Weak-motion-based attenuation relationships for Israel. *Geophysical Journal International*, **175**, 1127–1140.

Mezcua, J., García Blanco, R. M., & Rueda, J. 2008. On the strong ground motion attenuation in Spain. *Bulletin of the Seismological Society of America*, **98**(3), 1343–1353.

Midorikawa, S., & Ohtake, Y. 2004. Variance of peak ground acceleration and velocity in attenuation relationships. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 0325.

Milne, W. G. 1977. Seismic risk maps for Canada. *Page 930 of: Proceedings of Sixth World Conference on Earthquake Engineering*, vol. I. 2-508.

Milne, W. G., & Davenport, A. G. 1969. Distribution of earthquake risk in Canada. *Bulletin of the Seismological Society of America*, **59**(2), 729–754.

Mohammadioun, B. 1991. The prediction of response spectra for the anti-seismic design of structures specificity of data from intracontinential environments. *European Earthquake Engineering*, **V**(2), 8–17.

Mohammadioun, B. 1994a. Prediction of seismic motion at the bedrock from the strong-motion data currently available. *Pages 241–245 of: Proceedings of Tenth European Conference on Earthquake Engineering*, vol. 1.

Mohammadioun, G. 1994b. Calculation of site-adapted reference spectra from the statistical analysis of an extensive strong-motion data bank. *Pages 177–181 of: Proceedings of Tenth European Conference on Earthquake Engineering*, vol. 1.

Molas, G. L., & Yamazaki, F. 1995. Attenuation of earthquake ground motion in Japan including deep focus events. *Bulletin of the Seismological Society of America*, **85**(5), 1343–1358.

Molas, G. L., & Yamazaki, F. 1996. Attenuation of response spectra in Japan using new JMA records. *Bulletin of Earthquake Resistant Structure Research Center*, **29**(Mar), 115–128.

Monguilner, C. A., Ponti, N., & Pavoni, S. B. 2000a. Relationships between basic ground motion parameters for earthquakes of the Argentine western region. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper no. 1195.

Monguilner, C. A., Ponti, N., Pavoni, S. B., & Richarte, D. 2000b. Statistical characterization of the response spectra in the Argentine Republic. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper no. 1825.

Montalva, G. A. 2010 (Aug). *Site-specific seismic hazard analyses*. Ph.D. thesis, Washington State University.

Morasca, P., Malagnini, L., Akinci, A., Spallarossa, D., & Herrmann, R. B. 2006. Ground-motion scaling in the western Alps. *Journal of Seismology*, **10**(3), 315–333.

Morasca, P., Zolezzi, F., Spallarossa, D., & Luzi, L. 2008. Ground motion models for the Molise region (southern Italy). *Soil Dynamics and Earthquake Engineering*, **28**(3), 198–211.

Moss, R. E. S. 2009 (Nov). *Reduced uncertainty of ground motion prediction equations through Bayesian variance analysis*. PEER Report 2009/105. Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, USA.

Moss, R. E. S., & Der Kiureghian, A. 2006 (Apr). Incorporating parameter uncertainty into attenuation relationships. *In: Proceedings of the Eighth U.S. National Conference on Earthquake Engineering*. Paper no. 2010.

Motazedian, D., & Atkinson, G. 2005. Ground-motion relations for Puerto Rico. *Pages 61–80 of:* Mann, P. (ed), *Special paper 385: Active tectonics and seismic hazards of Puerto Rico, the Virgin Islands, and offshore areas*. The Geological Society of America.

Munson, C. G., & Thurber, C. H. 1997. Analysis of the attenuation of strong ground motion on the island of Hawaii. *Bulletin of the Seismological Society of America*, **87**(4), 945–960.

Musson, R. M. W., Marrow, P. C., & Winter, P. W. 1994 (May). *Attenuation of earthquake ground motion in the UK*. Tech. rept. AEA/CS/16422000/ZJ745/004. AEA Technology Consultancy Services (SRD) and British Geological Survey.

Nakajima, M., Choi, I.-K., Ohtori, Y., & Choun, Y.-S. 2007. Evaluation of seismic hazard curves and scenario earthquakes for Korean sites based on probabilistic seismic hazard analysis. *Nuclear Engineering and Design*, **237**(3), 277–288.

Nath, S. K., Vyas, M., Pal, I., Singh, A. K., Mukherjee, S., & Sengupta, P. 2005. Spectral attenuation models in the Sikkim Himalaya from the observed and simulated strong motion events in the region. *Current Science*, **88**(2), 295–303.

Niazi, M., & Bozorgnia, Y. 1991. Behaviour of near-source peak horizontal and vertical ground motions over SMART-1 array, Taiwan. *Bulletin of the Seismological Society of America*, **81**(3), 715–732.

Niazi, M., & Bozorgnia, Y. 1992. Behaviour of near-source vertical and horizontal response spectra at SMART-1 array, Taiwan. *Earthquake Engineering and Structural Dynamics*, **21**, 37–50.

Nowroozi, A. A. 2005. Attenuation relations for peak horizontal and vertical accelerations of earthquake ground motion in Iran: A preliminary analysis. *Journal of Seismology and Earthquake Engineering*, **7**(2), 109–128.

Nuttli, O. W., & Herrmann, R. B. 1987. Ground motion relations for eastern North American earthquakes. *Pages 231–241 of: Proceedings of the Third International Conference on Soil Dynamics & Earthquake Engineering*, vol. II.

Ohno, S., Ohta, T., Ikeura, T., & Takemura, M. 1993. Revision of attenuation formula considering the effect of fault size to evaluate strong motion spectra in near field. *Tectonophysics*, **218**, 69–81.

Ohno, S., Takemura, M., Niwa, M., & Takahashi, K. 1996. Intensity of strong ground motion on pre-quaternary stratum and surface soil amplifications during the 1995 Hyogo-ken Nanbu earthquake, Japan. *Journal of Physics of the Earth*, **44**(5), 623–648.

Ohsaki, Y., Watabe, M., & Tohdo, M. 1980a. Analyses on seismic ground motion parameters including vertical components. *Pages 97–104 of: Proceedings of Seventh World Conference on Earthquake Engineering*, vol. 2.

Ohsaki, Y., Sawada, Y., Hayashi, K., Ohmura, B., & Kumagai, C. 1980b. Spectral characteristics of hard rock motions. *Pages 231–238 of: Proceedings of Seventh World Conference on Earthquake Engineering*, vol. 2.

Ólafsson, S., & Sigbjörnsson, R. 1999. A theoretical attenuation model for earthquake-induced ground motion. *Journal of Earthquake Engineering*, **3**(3), 287–315.

Olszewska, D. 2006. Attenuation relations of ground motion acceleration response spectra for the Polkowice region. *Publications of the Institute of Geophysics of the Polish Academy of Sciences*, **M-29**(395).

Ordaz, M., & Reyes, C. 1999. Earthquake hazard in Mexico City: Observations versus computations. *Bulletin of the Seismological Society of America*, **89**(5), 1379–1383.

Ordaz, M., Jara, J. M., & Singh, S. K. 1989. *Riesgo sísmico y espectros de diseño en el estado de Guerrero*. Tech. rept. 8782/9745. UNAM Instituto de Ingeniería. In Spanish. Not seen, cited in Arroyo *et al.* (2010).

Ordaz, M., Singh, S. K., & Arciniega, A. 1994. Bayesian attenuation regressions: An application to Mexico City. *Geophysical Journal International*, **117**(2), 335–344.

Ornthammarath, T. 2010. *Influence of hazard modeling methods and the uncertainty of GMPEs on the results of probabilistic seismic hazard analysis*. Ph.D. thesis, ROSE School, University of Pavia, Italy.

Ornthammarath, T., Douglas, J., Sigbjörnsson, R., & Lai, C. G. 2010. Assessment of strong ground motion variability in Iceland. *In: Proceedings of Fourteenth European Conference on Earthquake Engineering*. Paper no. 1263.

Ornthammarath, T., Douglas, J., Sigbjörnsson, R., & Lai, C. G. 2011. Assessment of ground motion variability and its effects on seismic hazard analysis: A case study for Iceland. *Bulletin of Earthquake Engineering*, **9**. In press.

Orphal, D. L., & Lahoud, J. A. 1974. Prediction of peak ground motion from earthquakes. *Bulletin of the Seismological Society of America*, **64**(5), 1563–1574.

Özbey, C., Sari, A., Manuel, L., Erdik, M., & Fahjan, Y. 2004. An empirical attenuation relationship for northwestern Turkey ground motion using a random effects approach. *Soil Dynamics and Earthquake Engineering*, **24**(2), 115–125.

Pancha, A., & Taber, J. J. 1997. *Attenuation of weak ground motions: A report prepared for the New Zealand Earthquake Commission*. Tech. rept. School of Earth Sciences, Victoria University of Wellington, New Zealand. Not seen. Reported in Stafford (2006).

Pankow, K. L., & Pechmann, J. C. 2004. The SEA99 ground-motion predictive relations for extensional tectonic regimes: Revisions and a new peak ground velocity relation. *Bulletin of the Seismological Society of America*, **94**(1), 341–348.

Pankow, K. L., & Pechmann, J. C. 2006. Erratum: The SEA99 ground-motion predictive relations for extensional tectonic regimes: Revisions and a new peak ground velocity relation. *Bulletin of the Seismological Society of America*, **96**(1), 364.

Paolucci, R., Rovelli, A., Faccioli, E., Cauzzi, C., Finazzi, D., Vanini, M., Di Alessandro, C., & Calderoni, G. 2008. On the reliability of long period spectral ordinates from digital accelerograms. *Earthquake Engineering and Structural Dynamics*, **37**(5), 697–710.

Parvez, I. A., Gusev, A. A., Panza, G. F., & Petukhin, A. G. 2001. Preliminary determination of the interdependence among strong-motion amplitude, earthquake magnitude and hypocentral distance for the Himalayan region. *Geophysical Journal International*, **144**(3), 577–596.

Pathak, J., Paul, D. K., & Godbole, P. N. 2006 (Sep). ANN based attenuation relationship for estimation of PGA using Indian strong-motion data. *In: Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*. Paper no. 1132.

Peng, K., Xie, L., Li, S., Boore, D. M., Iwan, W. D., & Teng, T. L. 1985a. The near-source strong-motion accelerograms recorded by an experimental array in Tangshan, China. *Physics of the Earth and Planetary Interiors*, **38**, 92–109.

Peng, K.-Z., Wu, F. T., & Song, L. 1985b. Attenuation characteristics of peak horizontal acceleration in northeast and southwest China. *Earthquake Engineering and Structural Dynamics*, **13**(3), 337–350.

Perea, T., & Sordo, E. 1998. Direct response spectrum prediction including local site effects. *In: Proceedings of Eleventh European Conference on Earthquake Engineering*.

Peruš, I., & Fajfar, P. 2009 (Aug). How reliable are the ground motion prediction equations? *In: 20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)*. SMiRT 20-Division IV, Paper 1662.

Peruš, I., & Fajfar, P. 2010. Ground-motion prediction by a non-parametric approach. *Earthquake Engineering and Structural Dynamics*, **39**(12), 1395–1416.

Petrovski, D., & Marcellini, A. 1988. Prediction of seismic movement of a site: Statisical approach. *In: Proc. UN Sem. on Predict. of Earthquakes*. Lisbon, Portugal, 14–18 November.

Pétursson, G. G., & Vogfjörd, K. S. 2009. *Attenuation relations for near- and far-field peak ground motion (PGV, PGA) and new magnitude estimates for large earthquakes in SW-Iceland*. Tech. rept. VÍ 2009-012. Icelandic Meteorological Office, Reykjavik, Iceland.

PML. 1982. *British earthquakes*. Tech. rept. 115/82. Principia Mechanica Ltd., London. Not seen. Reported in Ambraseys *et al.* (1992).

PML. 1985. *Seismological studies for UK hazard analysis*. Tech. rept. 346/85. Principia Mechanica Ltd., London. Not seen. Reported in Ambraseys *et al.* (1992).

Popescu, E., Cioflan, C. O., Radulian, M., Placinta, A. O., & Moldovan, I. A. 2007 (Oct). Attenuation relations for the seismic ground motion induced by Vrancea intermediate-depth earthquakes. *In: International Symposium on Strong Vrancea Earthquakes and Risk Mitigation*.

Pousse, G., Berge-Thierry, C., Bonilla, L. F., & Bard, P.-Y. 2005. Eurocode 8 design response spectra evaluation using the K-Net Japanese database. *Journal of Earthquake Engineering*, **9**(4), 547–574.

Pousse, G., Bonilla, L. F., Cotton, F., & Margerin, L. 2006. Non stationary stochastic simulation of strong ground motion time histories including natural variability: Application to the K-net Japanese database. *Bulletin of the Seismological Society of America*, **96**(6), 2103Ű–2117.

Radu, C., Lungu, D., Demetriu, S., & Coman, O. 1994 (Sep). Recurrence, attenuation and dynamic amplification for intermediate depth Vrancea earthquakes. *Pages 1736–1745 of: Proceedings of the XXIV General Assembly of the ESC*, vol. III.

Raghu Kanth, S. T. G., & Iyengar, R. N. 2006. Seismic hazard estimation for Mumbai city. *Current Science*, **91**(11), 1486–1494.

Raghu Kanth, S. T. G., & Iyengar, R. N. 2007. Estimation of seismic spectral acceleration in peninsular India. *Journal of Earth System Science*, **116**(3), 199–214.

Ramazi, H. R., & Schenk, V. 1994 (Sep). Preliminary results obtained from strong ground motion analzses [sic] of Iranian earthquakes. *Pages 1762–1770 of: Proceedings of the XXIV General Assembly of the ESC*, vol. III.

Raoof, M., Herrmann, R. B., & Malagnini, L. 1999. Attenuation and excitation of three-component ground motion in southern California. *Bulletin of the Seismological Society of America*, **89**(4), 888–902.

Rathje, E. M., Faraj, F., Russell, S., & Bray, J. D. 2004. Empirical relationships for frequency content parameters of earthquake ground motions. *Earthquake Spectra*, **20**(1), 119–144.

Reyes, C. 1998. *El estado limite de servicio en el diseño sismico de edificios*. Ph.D. thesis, School of Engineering, National Autonomous University of Mexico (UNAM). In Spanish. Not seen, reported in Ordaz & Reyes (1999).

Rhoades, D. A. 1997. Estimation of attenuation relations for strong-motion data allowing for individual earthquake magnitude uncertainties. *Bulletin of the Seismological Society of America*, **87**(6), 1674–1678.

Richter, C. F. 1958. *Elementary Seismology*. San Francisco, USA: Freeman and Co.

Rinaldis, D., Berardi, R., Theodulidis, N., & Margaris, B. 1998. Empirical predictive models based on a joint Italian & Greek strong-motion database: I, peak ground acceleration and velocity. *In: Proceedings of Eleventh European Conference on Earthquake Engineering*.

Rodriguez-Marek, A., & Montalva, G. 2010 (Feb). *Uniform hazard spectra for site-specific applications including uncertainties in site-response*. Final technical report. Washington State University, USA. USGS award number 08HQGR0086.

Rogers, A. M., Perkins, D. M., Hampson, D. B., & Campbell, K. W. 1991. Investigations of peak acceleration data for site effects. *Pages 229–236 of: Proceedings of the Fourth International Conference on Seismic Zonation*, vol. II.

Romeo, R. W., Tranfaglia, G., & Castenetto, S. 1996. Engineering-developed relations derived from the strongest instrumentally-detected Italian earthquakes. *In: Proceedings of Eleventh World Conference on Earthquake Engineering*. Paper no. 1466.

Ruiz, S., & Saragoni, G. R. 2005 (Nov). Formulas de atenuación para la subducción de Chile considerando los dos mecanismos de sismogenesis y los efectos del suelo. *In: Congreso Chileno de Sismología e Ingeniería Antisísmica, Novenas Jornadas*. No. 01-07. In Spanish.

Rupakhety, R., & Sigbjörnsson, R. 2009. Ground-motion prediction equations (GMPEs) for inelastic response and structural behaviour factors. *Bulletin of Earthquake Engineering*, **7**(3), 637–659.

Sabetta, F., & Pugliese, A. 1987. Attenuation of peak horizontal acceleration and velocity from Italian strong-motion records. *Bulletin of the Seismological Society of America*, **77**(5), 1491–1513.

Sabetta, F., & Pugliese, A. 1996. Estimation of response spectra and simulation of nonstationary earthquake ground motions. *Bulletin of the Seismological Society of America*, **86**(2), 337–352.

Sadeghi, H., Shooshtari, A., & Jaladat, M. 2010. Prediction of horizontal response spectra of strong ground motions in Iran and its regions. *In: Proceedings of the Ninth U.S. National and 10th Canadian Conference on Earthquake Engineering: Reaching Beyond Borders*. Paper no. 861.

Sadigh, K., Youngs, R. R., & Power, M. S. 1978. A study of attenuation of peak horizontal accelerations for moderately strong earthquakes. *Pages 243–250 of: Proceedings of Sixth European Conference on Earthquake Engineering*, vol. 1.

Sadigh, K., Chang, C.-Y., Abrahamson, N. A., Chiou, S. J., & Power, M. S. 1993 (Mar). Specification of long-period ground motions: Updated attenuation relationships for rock site conditions and adjustment factors for near-fault effects. *Pages 59–70 of: Proceedings of ATC-17-1 Seminar on Seismic Isolation, Passive Energy Dissipation, and Active Control*.

Sadigh, K., Chang, C.-Y., Egan, J. A., Makdisi, F., & Youngs, R. R. 1997. Attenuation relationships for shallow crustal earthquakes based on California strong motion data. *Seismological Research Letters*, **68**(1), 180–189.

Sadigh, R. K., & Egan, J. A. 1998. Updated relationships for horizontal peak ground velocity and peak ground displacement for shallow crustal earthquakes. *In: Proceedings of the Sixth U.S. National Conference on Earthquake Engineering*.

Saffari, H., Kuwata, Y., Takada, S., & Mahdavian, A. 2010. Spectral acceleration attenuation for seismic hazard analysis in Iran. *In: Proceedings of the Ninth U.S. National and 10th Canadian Conference on Earthquake Engineering: Reaching Beyond Borders*. Paper no. 867.

Saini, S., Sharma, M. L., & Mukhopadhyay, S. 2002 (Dec). Strong ground motion empirical attenuation relationship for seismic hazard estimation in Himalaya region. *Pages 143–150 of: 12th Symposium on Earthquake Engineering*, vol. I.

Sakamoto, S., Uchiyama, Y., & Midorikawa, S. 2006 (Apr). Variance of response spectra in attenuation relationship. *In: Proceedings of the Eighth U.S. National Conference on Earthquake Engineering*. Paper no. 471.

Sanchez, A. R., & Jara, J. M. 2001. Estimación del peligro sísmico de Morelia. *Ciencia nicolaita*, **29**, 63–76. Not seen. Cited in Jara-Guerrero *et al.* (2007). In Spanish.

Sarma, S. K., & Free, M. W. 1995 (November). The comparison of attenuation relationships for peak horizontal acceleration in intraplate regions. *Pages 175–184 of: Pacific Conference on Earthquake Engineering*, vol. 2.

Sarma, S. K., & Srbulov, M. 1996. A simplified method for prediction of kinematic soil-foundation interaction effects on peak horizontal acceleration of a rigid foundation. *Earthquake Engineering and Structural Dynamics*, **25**(8), 815–836.

Sarma, S. K., & Srbulov, M. 1998. A uniform estimation of some basic ground motion parameters. *Journal of Earthquake Engineering*, **2**(2), 267–287.

Savy, J. B., Boussonnade, A. C., Mensing, R. W., & Short, C. M. 1993 (Jun). *Eastern U.S. seismic hazard characterization update*. Tech. rept. UCRL-ID-115111. Lawrence Livermore National Laboratory, USA.

Scasserra, G., Stewart, J. P., Bazzurro, P., Lanzo, G., & Mollaioli, F. 2009. A comparison of NGA ground-motion prediction equations to Italian data. *Bulletin of the Seismological Society of America*, **99**(5), 2961–2978.

Schenk, V. 1982. Peak particle ground motions in earthquake near-field. *Pages 211–217 of: Proceedings of Seventh European Conference on Earthquake Engineering*, vol. 2.

Schenk, V. 1984. Relations between ground motions and earthquake magnitude, focal distance and epicentral intensity. *Engineering Geology*, **20**(1/2), 143–151.

Scherbaum, F., Cotton, F., & Smit, P. 2004. On the use of response spectral-reference data for the selection and ranking of ground-motion models for seismic-hazard analysis in regions of moderate seismicity: The case of rock motion. *Bulletin of the Seismological Society of America*, **94**(6), 2164–2185.

Schmidt, V., Dahle, A., & Bungum, H. 1997 (Nov.). *Costa Rican spectral strong motion attenuation*. Tech. rept. NORSAR, Kjeller, Norway. Reduction of Natural Disasters in central America Earthquake Preparedness and Hazard Mitigation Phase II: 1996–2000, Part 2.

Schnabel, P. B., & Seed, H. B. 1973. Accelerations in rock for earthquakes in the western United States. *Bulletin of the Seismological Society of America*, **63**(2), 501–516.

Schwarz, J., Ende, C., Habenberger, J., Lang, D. H., Baumbach, M., Grosser, H., Milereit, C., Karakisa, S., & Zünbül, S. 2002 (Sep). Horizontal and vertical response spectra on the basis of strong-motion recordings from the 1999 Turkey earthquakes. *In: Proceedings of the XXVIII General Assembly of the European Seismological Commission (ESC)*.

Scognamiglio, L., Malagnini, L., & Akinci, A. 2005. Ground-motion scaling in eastern Sicily, Italy. *Bulletin of the Seismological Society of America*, **95**(2), 568–578.

Seed, H. B., Murarka, R., Lysmer, J., & Idriss, I. M. 1976. Relationships of maximum acceleration, maximum velocity, distance from source, and local site conditions for moderately strong earthquakes. *Bulletin of the Seismological Society of America*, **66**(4), 1323–1342.

Selcuk, L., Selcuk, A. S., & Beyaz, T. 2010. Probabilistic seismic hazard assessment for Lake Van basin, Turkey. *Natural Hazards*, **54**(3), 949–965.

Sen, M. K. 1990 (May). Deep structural complexity and site response in Los Angeles basin. *Pages 545–553 of: Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*, vol. 1.

Shabestari, K. T., & Yamazaki, F. 2000. Attenuation relation of response spectra in Japan considering site-specific term. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper No. 1432.

Shabestari, T. K., & Yamazaki, F. 1998. Attenuation of JMA seismic intensity using recent JMA records. *Pages 529–534 of: Proceedings of the 10th Japan Earthquake Engineering Symposium*, vol. 1. Not seen. Reported in Shabestari & Yamazaki (2000).

Sharma, M., & Bungum, H. 2006. New strong ground-motion spectral acceleration relations for the Himalayan region. *In: Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*. Paper number 1459.

Sharma, M. L. 1998. Attenuation relationship for estimation of peak ground horizontal acceleration using data from strong-motion arrays in India. *Bulletin of the Seismological Society of America*, **88**(4), 1063–1069.

Sharma, M. L. 2000. Attenuation relationship for estimation of peak ground vertical acceleration using data from strong motion arrays in India. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper No. 1964.

Sharma, M. L., Douglas, J., Bungum, H., & Kotadia, J. 2009. Ground-motion prediction equations based on data from the Himalayan and Zagros regions. *Journal of Earthquake Engineering*, **13**(8), 1191–1210.

Shi, S., & Shen, J. 2003. A study on attenuation relations of strong earth movements in Shanghai and its adjacent area. *Earthquake Research in China*, **19**, 315–323. In Chinese. Not seen. Cited in Cole *et al.* (2008).

Si, H., & Midorikawa, S. 1999. New attenuation relationships for peak ground acceleration and velocity considering effects of fault type and site condition. *Journal of structural and construction engineering, aij*, **523**, 63–70. In Japanese with English abstract. Not seen.

Si, H., & Midorikawa, S. 2000. New attenuation relations for peak ground acceleration and velocity considering effects of fault type and site condition. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper No. 0532.

Sigbjörnsson, R. 1990. Strong motion measurements in Iceland and seismic risk assessment. *Pages 215–222 of: Proceedings of Ninth European Conference on Earthquake Engineering*, vol. 10-A.

Sigbjörnsson, R., & Ambraseys, N. N. 2003. Uncertainty analysis of strong ground motion. *Bulletin of Earthquake Engineering*, **1**(3), 321–347.

Sigbjörnsson, R., & Baldvinsson, G. I. 1992. Seismic hazard and recordings of strong ground motion in Iceland. *Pages 419–424 of: Proceedings of Tenth World Conference on Earthquake Engineering*, vol. 1. Rotterdam, The Netherlands: A. A. Balkema. Madrid, Spain. 19–24 July.

Silva, W., & Abrahamson, N. A. 1992. Quantification of long period strong ground motion attenuation for engineering design. *In:* Huang, M. J. (ed), *Proceedings of (strong Motion Instrumentation Program) smip92 seminar on seismological and engineering implications of recent strong-motion data*. California Division of Mines and Geology, Sacramento, USA.

Silva, W., Gregor, N., & Darragh, R. 2002 (Nov). *Development of regional hard rock attenuation relations for central and eastern North America*. Tech. rept. Pacific Engineering and Analysis.

Simpson, K. A. 1996. *Attenuation of strong ground-motion incorporating near-surface foundation conditions*. Ph.D. thesis, University of London.

Singh, R. P., Aman, A., & Prasad, Y. J. J. 1996. Attenuation relations for strong seismic ground motion in the Himalayan region. *Pure and Applied Geophysics*, **147**(1), 161–180.

Singh, S. K., Mena, E., Castro, R., & Carmona, C. 1987. Empirical prediction of ground motion in Mexico City from coastal earthquakes. *Bulletin of the Seismological Society of America*, **77**(5), 1862–1867.

Singh, S. K., Gutierreez, C., Arboleda, J., & Ordaz, M. 1993. *Peligro sísmico en El Salvador*. Tech. rept. Universidad Nacional Autónoma de México, México. Not seen. Reported in Bommer *et al.* (1996).

Skarlatoudis, A., Theodulidis, N., Papaioannou, C., & Roumelioti, Z. 2004. The dependence of peak horizontal acceleration on magnitude and distance for small magnitude earthquakes in Greece. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 1857.

Skarlatoudis, A. A., Papazachos, C. B., Margaris, B. N., Theodulidis, N., Papaioannou, C., Kalogeras, I., Scordilis, E. M., & Karakostas, V. 2003. Empirical peak ground-motion predictive relations for shallow earthquake in Greece. *Bulletin of the Seismological Society of America*, **93**(6), 2591–2603.

Slejko, D., Javakhishvili, Z., Rebez, A., Santulin, M., Elashvili, M., Bragato, P. L., Godoladze, T., & Garcia, J. 2008. Seismic hazard assessment for the Tbilisi test area (eastern Georgia). *Bollettino di Geofisica Teorica ed Applicata*, **49**(1), 37–57.

Smit, P. 1998 (Sep). Strong motion attenuation model for central Europe. *In: Proceedings of Eleventh European Conference on Earthquake Engineering*. smisma.

Smit, P. 2000 (Dec). Personal communication 4/12/2000.

Smit, P., Arzoumanian, V., Javakhishvili, Z., Arefiev, S., Mayer-Rosa, D., Balassanian, S., & Chelidze, T. 2000. The digital accelerograph network in the Caucasus. *In:* Balassanian, S. (ed), *Earthquake Hazard and Seismic Risk Reduction — Advances in Natural and Technological Hazards Research*. Kluwer Academic Publishers. Presented at 2nd International Conference on Earthquake Hazard and Seismic Risk Reduction, Yerevan, Armenia, 15/9/1998–21/9/1998.

Sobhaninejad, G., Noorzad, A., & Ansari, A. 2007 (Jun). Genetic algorithm (GA): A new approach in estimating strong ground motion attenuation relations. *In: Proceedings of the Fourth International Conference on Earthquake Geotechnical Engineering*. Paper no. 1313.

Sokolov, V. 1997. Empirical models for estimating Fourier-amplitude spectra of ground acceleration in the northern Caucasus (Racha seismogenic zone). *Bulletin of the Seismological Society of America*, **87**(6), 1401–1412.

Sokolov, V., Loh, C.-H., & Wen, K.-L. 2000. Empirical model for estimating Fourier amplitude spectra of ground acceleration in Taiwan region. *Earthquake Engineering and Structural Dynamics*, **29**(3), 339–357.

Sokolov, V., Bonjer, K.-P., Oncescu, M., & Rizescu, M. 2005. Hard rock spectral models for intermediate-depth Vrancea, Romania, earthquakes. *Bulletin of the Seismological Society of America*, **95**(5), 1749–1765.

Sokolov, V., Bonjer, K.-P., Wenzel, F., Grecu, B., & Radulian, M. 2008. Ground-motion prediction equations for the intermediate depth Vrancea (Romania) earthquakes. *Bulletin of Earthquake Engineering*, **6**, 367–388.

Sokolov, V. Y. 1998. Spectral parameters of the ground motions in Caucasian seismogenic zones. *Bulletin of the Seismological Society of America*, **88**(6), 1438–1444.

Somerville, P., Collins, N., Abrahamson, N., Graves, R., & Saikia, C. 2001 (Jun). *Ground motion attenuation relations for the central and eastern United States*. Tech. rept. Research supported by the U.S. Geological Survey, under award number 99HQGR0098.

Somerville, P., Graves, R., Collins, N., Song, S. G., Ni, S., & Cummins, P. 2009 (Dec). Source and ground motion models of Australian earthquakes. *In: Proceedings of the 2009 Annual Conference of the Australian Earthquake Engineering Society*.

Souriau, A. 2006. Quantifying felt events: A joint analysis of intensities, accelerations and dominant frequencies. *Journal of Seismology*, **10**(1), 23–38.

Spudich, P., & Boore, D. M. 2005. Erratum: SEA99: A revised ground-motion prediction relation for use in extensional tectonic regimes. *Bulletin of the Seismological Society of America*, **95**(3), 1209.

Spudich, P., Fletcher, J., Hellweg, M., Boatwright, J., Sullivan, C., Joyner, W., Hanks, T., Boore, D., McGarr, A., Baker, L., & Lindh, A. 1996. *Earthquake ground motions in extensional tectonic regimes*. Open-File Report 96-292. U.S. Geological Survey. Not seen. Reported in Spudich *et al.* (1997).

Spudich, P., Fletcher, J. B., Hellweg, M., Boatwright, J., Sullivan, C., Joyner, W. B., Hanks, T. C., Boore, D. M., McGarr, A., Baker, L. M., & Lindh, A. G. 1997. SEA96 — A new predictive relation for earthquake ground motions in extensional tectonic regimes. *Seismological Research Letters*, **68**(1), 190–198.

Spudich, P., Joyner, W. B., Lindh, A. G., Boore, D. M., Margaris, B. M., & Fletcher, J. B. 1999. SEA99: A revised ground motion prediction relation for use in extensional tectonic regimes. *Bulletin of the Seismological Society of America*, **89**(5), 1156–1170.

Srinivasan, C., Sharma, M. L., Kotadia, J., & Willy, Y. A. 2008. Peak ground horizontal acceleration attenuation relationship for low magnitudes at short distances in south Indian region. *In: Proceedings of Fourteenth World Conference on Earthquake Engineering*. Paper no. 02-0135.

Stafford, P. J. 2006 (Feb). *Engineering seismological studies and seismic design criteria for the Buller region, South Island, New Zealand*. Ph.D. thesis, University of Canterbury, Christchurch, New Zealand.

Stafford, P. J., Berrill, J. B., & Pettinga, J. R. 2009. New predictive equations for Arias intensity from crustal earthquakes in New Zealand. *Journal of Seismology*, **13**(1), 31–52.

Stamatovska, S. 2002 (Sep). A new azimuth dependent empirical strong motion model for Vranchea subduction zone. *In: Proceedings of Twelfth European Conference on Earthquake Engineering*. Paper reference 324.

Stamatovska, S., & Petrovski, D. 1991. Ground motion parameters based on data obtained from strong earthquake records. *In: National Progress Report of Yugoslavia, UNDP/UNESCO Project Rep/88/004, Task Group 3, Second Meeting*. Zagreb, Yugoslavia: Geophysical Institute.

Stamatovska, S., & Petrovski, D. 1996. Empirical attenuation acceleration laws for Vrancea intermediate earthquakes. *In: Proceedings of Eleventh World Conference on Earthquake Engineering*. Paper no. 146.

Steinberg, V. V., Saks, M. V., Aptikaev, F. F., *et al.* . 1993. Methods of seismic ground motion estimation (handbook). *Pages 5–97 of: Voprosy inzhenernoi seismologii. iss. 34. nauka*. In Russian. Not seen. Cited by Lyubushin & Parvez (2010).

Sun, F., & Peng, K. 1993. Attenuation of strong ground motion in western U.S.A. *Earthquake Research in China*, **7**(1), 119–131.

Sunuwar, L., Cuadra, C., & Karkee, M. B. 2004. Strong ground motion attenuation in the Sea of Japan (Okhotsk-Amur plates boundary) region. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 0197.

Takahashi, T., Kobayashi, S., Fukushima, Y., Zhao, J. X., Nakamura, H., & Somerville, P. G. 2000 (Nov). A spectral attenuation model for Japan using strong motion data base. *In: Proceedings of the Sixth International Conference on Seismic Zonation*.

Takahashi, T., Asano, A., Saiki, T., Okada, H., Irikura, K., Zhao, J. X., Zhang, J., Thio, H. K., Somerville, P. G., Fukushima, Y., & Fukushima, Y. 2004. Attenuation models for response spectra derived from Japanese strong-motion records accounting for tectonic source types. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 1271.

Takahashi, T., Asano, A., Ono, Y., Ogawa, H., Zhao, J. X., Zhang, J., Fukushima, Y., Irikura, K., Thio, H. K., Somerville, P. G., & Fukushima, Y. 2005 (Aug). Attenuation relations of strong motion in Japan using site classification based on predominant period. *In: 18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)*. Paper SMiRT18-K02-1.

Tamura, K., Sasaki, Y., & Aizawa, K. 1990 (May). Attenuation characteristics of ground motions in the period range of 2 to 20 seconds — for application to the seismic design of long-period structures. *Pages 495–504 of: Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*, vol. 1.

Tavakoli, B., & Pezeshk, S. 2005. Empirical-stochastic ground-motion prediction for eastern North America. *Bulletin of the Seismological Society of America*, **95**(6), 2283–2296.

Tavakoli, B., & Pezeshk, S. 2007. A new approach to estimate a mixed model-based ground motion prediction equation. *Earthquake Spectra*, **23**(3), 665–684.

Taylor Castillo, W., Santos Lopez, P., Dahle, A., & Bungum, H. 1992 (Nov.). *Digitization of strong motion data and estimation of PGA attenuation*. Tech. rept. NORSAR, Kjeller, Norway. Reduction of Natural Disasters in central America Earthquake Preparedness and Hazard Mitigation Seismic Zonation and Earthquake Hazard Assessment.

Tejeda-Jácome, J., & Chávez-García, F. J. 2007. Empirical ground-motion estimation equations in Colima from weak motion records. *ISET Journal of Earthquake Technology*, **44**(3–4), 409–420.

Tento, A., Franceschina, L., & Marcellini, A. 1992. Expected ground motion evaluation for Italian sites. *Pages 489–494 of: Proceedings of Tenth World Conference on Earthquake Engineering*, vol. 1.

Theodulidis, N. P., & Papazachos, B. C. 1992. Dependence of strong ground motion on magnitude-distance, site geology and macroseismic intensity for shallow earthquakes in Greece: I, peak horizontal acceleration, velocity and displacement. *Soil Dynamics and Earthquake Engineering*, **11**, 387–402.

Theodulidis, N. P., & Papazachos, B. C. 1994. Dependence of strong ground motion on magnitude-distance, site geology and macroseismic intensity for shallow earthquakes in Greece: II horizontal pseudovelocity. *Soil Dynamics and Earthquake Engineering*, **13**(5), 317–343.

Tong, H., & Katayama, T. 1988. Peak acceleration attenuation by eliminating the ill-effect of the correlation between magnitude and epicentral distance. *Pages 349–354 of: Proceedings of Ninth World Conference on Earthquake Engineering*, vol. II.

Toro, G. R. 2002 (Jun). *Modification of the Toro et al. (1997) attenuation equations for large magnitudes and short distances*. Tech. rept. Risk Engineering.

Toro, G. R., & McGuire, R. K. 1987. An investigation into earthquake ground motion characteristics in eastern North America. *Bulletin of the Seismological Society of America*, **77**(2), 468–489.

Toro, G. R., & Silva, W. J. 2001 (Jan). *Scenario earthquakes for Saint Louis, MO, and Memphis, TN, and seismic hazard maps for the central United States region including the effect of site conditions*. Tech. rept. Research supported by the U.S. Geological Survey (USGS), under award number 1434-HQ-97-GR-02981.

Trifunac, M. D. 1976. Preliminary analysis of the peaks of strong earthquake ground motion – dependence of peaks on earthquake magnitude, epicentral distance, and recording site conditions. *Bulletin of the Seismological Society of America*, **66**(1), 189–219.

Trifunac, M. D. 1977. Forecasting the spectral amplitudes of strong earthquake ground motion. *Pages 139–152 of: Proceedings of Sixth World Conference on Earthquake Engineering*, vol. I.

Trifunac, M. D. 1978. Response spectra of earthquake ground motions. *Journal of the Engineering Mechanics Division, ASCE*, **104**(EM5), 1081–1097.

Trifunac, M. D. 1980. Effects of site geology on amplitudes of strong motion. *Pages 145–152 of: Proceedings of Seventh World Conference on Earthquake Engineering*, vol. 2.

Trifunac, M. D., & Anderson, J. G. 1977. *Preliminary empirical models for scaling absolute acceleration spectra*. Tech. rept. 77-03. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

Trifunac, M. D., & Anderson, J. G. 1978a. *Preliminary empirical models for scaling pseudo relative velocity spectra*. Tech. rept. 78-04. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

Trifunac, M. D., & Anderson, J. G. 1978b. *Preliminary empirical models for scaling relative velocity spectra*. Tech. rept. 78-05. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

Trifunac, M. D., & Brady, A. G. 1975. On the correlation of peak acceleration of strong motion with earthquake magnitude, epicentral distance and site conditions. *Pages 43–52 of: Proceedings of the U.S. National Conference on Earthquake Engineering*.

Trifunac, M. D., & Brady, A. G. 1976. Correlations of peak acceleration, velocity and displacement with earthquake magnitude, distance and site conditions. *Earthquake Engineering and Structural Dynamics*, **4**(5), 455–471.

Trifunac, M. D., & Lee, V. W. 1979. *Dependence of pseudo relative velocity spectra of strong motion acceleration on depth of sedimentary deposits*. Tech. rept. 79-02. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

Trifunac, M. D., & Lee, V. W. 1985. *Preliminary empirical model for scaling pseudo relative velocity spectra of strong earthquake acceleration in terms of magnitude, distance, site intensity and recording site condition*. Tech. rept. 85-04. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

Trifunac, M. D., & Lee, V. W. 1989. Empirical models for scaling pseudo relative velocity spectra of strong earthquake accelerations in terms of magnitude, distance, site intensity and recording site conditions. *Soil Dynamics and Earthquake Engineering*, **8**(3), 126–144.

Tromans, I. 2004 (Jan). *Behaviour of buried water supply pipelines in earthquake zones*. Ph.D. thesis, University of London.

Tromans, I. J., & Bommer, J. J. 2002 (Sep). The attenuation of strong-motion peaks in Europe. *In: Proceedings of Twelfth European Conference on Earthquake Engineering*. Paper no. 394.

Tsai, Y. B., Brady, F. W., & Cluff, L. S. 1990 (May). An integrated approach for characterization of ground motions in PG&E's long term seismic program for Diablo Canyon. *Pages 597–606 of: Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*, vol. 1.

Tuluka, M. 2007. An estimate of the attenuation relationship for strong ground motion in the Kivu Province, Western Rift Valley of Africa. *Physics of the Earth and Planetary Interiors*, **162**, 13–21.

Ulusay, R., Tuncay, E., Sonmez, H., & Gokceoglu, C. 2004. An attenuation relationship based on Turkish strong motion data and iso-acceleration map of Turkey. *Engineering Geology*, **74**(3-4), 265–291.

Ulutas, E., & Ozer, M. F. 2010. Empirical attenuation relationship of peak ground acceleration for eastern Marmara region in Turkey. *The Arabian Journal for Science and Engineering*, **35**(1A), 187–203.

Vives, V., & Canas, J.A. 1992. Anelastic attenuation and pseudoacceleration relations in eastern Iberia. *Pages 299–304 of: Proceedings of Tenth World Conference on Earthquake Engineering*, vol. 1.

Wald, D. J., Worden, B. C., Quitoriano, V., & Pankow, K. L. 2005. *ShakeMap ® manual*. Technical Manual, users guide, and software guide Version 1.0. USGS Techniques and Methods 12-A1.

Wang, B.-Q., Wu, F. T., & Bian, Y.-J. 1999. Attenuation characteristics of peak acceleration in north China and comparison with those in the eastern part of North America. *Acta Seismologica Sinica*, **12**(1), 26–34.

Wang, G., & Tao, X. 2000 (Nov). A new two-stage procedure for fitting attenuation relationship of strong ground motion. *In: Proceedings of the Sixth International Conference on Seismic Zonation*.

Wang, M., & Takada, T. 2009. A Bayesian framework for prediction of seismic ground motion. *Bulletin of the Seismological Society of America*, **99**(4), 2348–2364.

Weisburg, S. 1985. *Applied Linear Regression*. 2nd edn. John Wiley & Sons.

Wells, D. L., & Coppersmith, K. J. 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America*, **84**(4), 974–1002.

Wiggins Jr., J. H. 1964. Construction of strong motion response spectra from magnitude and distance data. *Bulletin of the Seismological Society of America*, **54**(5), 1257–1269.

Wills, C. J., Petersen, M., Bryant, W. A., Reichle, M., Saucedo, G. J., Tan, S., Taylor, G., & Treiman, J. 2000. A site-conditions map for California based on geology and shear-wave velocity. *Bulletin of the Seismological Society of America*, **90**(6B), S187–S208.

Wu, Y.-M., Shin, T.-C., & Chang, C.-H. 2001. Near real-time mapping of peak ground acceleration and peak ground velocity following a strong earthquake. *Bulletin of the Seismological Society of America*, **91**(5), 1218–1228.

Xiang, J., & Gao, D. 1994. The attenuation law of horizontal peak acceleration on the rock site in Yunnan area. *Earthquake Research in China*, **8**(4), 509–516.

Xu, Z., Shen, X., & Hong, J. 1984. Attenuation relation of ground motion in northern China. *Pages 335–342 of: Proceedings of Eighth World Conference on Earthquake Engineering*, vol. II.

Yamabe, K., & Kanai, K. 1988. An empirical formula on the attenuation of the maximum acceleration of earthquake motions. *Pages 337–342 of: Proceedings of Ninth World Conference on Earthquake Engineering*, vol. II.

Yamazaki, F., Wakamatsu, K., Onishi, J., & Shabestari, K. T. 2000. Relationship between geomorphological land classification and site amplification ratio based on JMA strong motion records. *Soil Dynamics and Earthquake Engineering*, **19**(1), 41–53.

Yokota, H., Shiba, K., & Okada, K. 1988. The characteristics of underground earthquake motions observed in the mud stone layer in Tokyo. *Pages 429–434 of: Proceedings of Ninth World Conference on Earthquake Engineering*, vol. II.

Youngs, R. R., Day, S. M., & Stevens, J. L. 1988. Near field ground motions on rock for large subduction earthquakes. *Pages 445–462 of: Proceedings of Earthquake Engineering & Soil Dynamics II*. Geotechnical Division, ASCE.

Youngs, R. R., Abrahamson, N., Makdisi, F. I., & Sadigh, K. 1995. Magnitude-dependent variance of peak ground acceleration. *Bulletin of the Seismological Society of America*, **85**(4), 1161–1176.

Youngs, R. R., Chiou, S.-J., Silva, W. J., & Humphrey, J. R. 1997. Strong ground motion attenuation relationships for subduction zone earthquakes. *Seismological Research Letters*, **68**(1), 58–73.

Yu, Y., & Hu, Y. 2004. Empirical long-period response spectral attenuation relations based on southern California digital broad-band recordings. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 0344.

Yuzawa, Y., & Kudo, K. 2008. Empirical estimation of long-period (1–$10\,\mathrm{sec.}$) earthquake ground motion on hard rocks. *In: Proceedings of Fourteenth World Conference on Earthquake Engineering*. Paper no. S10-057.

Zafarani, H., Mousavi, M., Noorzad, A., & Ansari, A. 2008. Calibration of the specific barrier model to Iranian plateau earthquakes and development of physically based attenuation relationships for Iran. *Soil Dynamics and Earthquake Engineering*, **28**(7), 550–576.

Zare, M., & Sabzali, S. 2006. Spectral attenuation of strong motions in Iran. *Pages 749–758 of: Proceedings of Third International Symposium on the Effects of Surface Geology on Seismic Motion*, vol. 1. Paper number 146.

Zaré, M., Ghafory-Ashtiany, M., & Bard, P.-Y. 1999. Attenuation law for the strong-motions in Iran. *Pages 345–354 of: Proceedings of the Third International Conference on Seismology and Earthquake Engineering, Tehran*, vol. 1.

Zhao, J. X. 2010. Geometric spreading functions and modeling of volcanic zones for strong-motion attenuation models derived from records in Japan. *Bulletin of the Seismological Society of America*, **100**(2), 712–732.

Zhao, J. X., Dowrick, D. J., & McVerry, G. H. 1997. Attenuation of peak ground acceleration in New Zealand earthquakes. *Bulletin of the New Zealand National Society for Earthquake Engineering*, **30**(2), 133–158.

Zhao, J. X., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Thio, H. K., Somerville, P. G., Fukushima, Y., & Fukushima, Y. 2006. Attenuation relations of strong ground motion in Japan using site classification based on predominant period. *Bulletin of the Seismological Society of America*, **96**(3), 898–913.

Zheng, S., & Wong, Y. L. 2004. Seismic ground motion relationships in southern China based on stochastic finite-fault model. *Earthquake Engineering and Engineering Vibration*, **3**(1), 11–21.

Zonno, G., & Montaldo, V. 2002. Analysis of strong ground motions to evaluate regional attenuation relationships. *Annals of Geophysics*, **45**(3–4), 439–454.

PEER REPORTS

PEER reports are available individually or by yearly subscription. PEER reports can be ordered at http://peer.berkeley.edu/publications/peer_reports.html or by contacting the Pacific Earthquake Engineering Research Center, 325 Davis Hall mail code 1792, Berkeley, CA 94720. Tel.: (510) 642-3437; Fax: (510) 665-1655; Email: peer_editor@berkeley.edu

PEER 2011/03 *New Ground Motion Selection Procedures and Selected Motions for the PEER Transportation Research Program.* Jack W. Baker, Ting Lin, Shrey K. Shahi, and Nirmal Jayaram. March 2011.

PEER 2011/02 *A Bayesian Network Methodology for Infrastructure Seismic Risk Assessment and Decision Support.* Michelle T. Bensi, Armen Der Kiureghian, and Daniel Straub. March 2011.

PEER 2011/01 *Demand Fragility Surfaces for Bridges in Liquefied and Laterally Spreading Ground.* Scott J. Brandenberg, Jian Zhang, Pirooz Kashighandi, Yili Huo, and Minxing Zhao. March 2011.

PEER 2010/05 *Guidelines for Performance-Based Seismic Design of Tall Buildings.* Developed by the Tall Buildings Initiative. November 2010.

PEER 2010/04 *Application Guide for the Design of Flexible and Rigid Bus Connections between Substation Equipment Subjected to Earthquakes.* Jean-Bernard Dastous and Armen Der Kiureghian. September 2010.

PEER 2010/03 *Shear Wave Velocity as a Statistical Function of Standard Penetration Test Resistance and Vertical Effective Stress at Caltrans Bridge Sites.* Scott J. Brandenberg, Naresh Bellana, and Thomas Shantz. June 2010.

PEER 2010/02 *Stochastic Modeling and Simulation of Ground Motions for Performance-Based Earthquake Engineering.* Sanaz Rezaeian and Armen Der Kiureghian. June 2010.

PEER 2010/01 *Structural Response and Cost Characterization of Bridge Construction Using Seismic Performance Enhancement Strategies.* Ady Aviram, Božidar Stojadinović, Gustavo J. Parra-Montesinos, and Kevin R. Mackie. March 2010.

PEER 2009/03 *The Integration of Experimental and Simulation Data in the Study of Reinforced Concrete Bridge Systems Including Soil-Foundation-Structure Interaction.* Matthew Dryden and Gregory L. Fenves. November 2009.

PEER 2009/02 *Improving Earthquake Mitigation through Innovations and Applications in Seismic Science, Engineering, Communication, and Response. Proceedings of a U.S.-Iran Seismic Workshop.* October 2009.

PEER 2009/01 *Evaluation of Ground Motion Selection and Modification Methods: Predicting Median Interstory Drift Response of Buildings.* Curt B. Haselton, Ed. June 2009.

PEER 2008/10 *Technical Manual for Strata.* Albert R. Kottke and Ellen M. Rathje. February 2009.

PEER 2008/09 *NGA Model for Average Horizontal Component of Peak Ground Motion and Response Spectra.* Brian S.-J. Chiou and Robert R. Youngs. November 2008.

PEER 2008/08 *Toward Earthquake-Resistant Design of Concentrically Braced Steel Structures.* Patxi Uriz and Stephen A. Mahin. November 2008.

PEER 2008/07 *Using OpenSees for Performance-Based Evaluation of Bridges on Liquefiable Soils.* Stephen L. Kramer, Pedro Arduino, and HyungSuk Shin. November 2008.

PEER 2008/06 *Shaking Table Tests and Numerical Investigation of Self-Centering Reinforced Concrete Bridge Columns.* Hyung IL Jeong, Junichi Sakai, and Stephen A. Mahin. September 2008.

PEER 2008/05 *Performance-Based Earthquake Engineering Design Evaluation Procedure for Bridge Foundations Undergoing Liquefaction-Induced Lateral Ground Displacement.* Christian A. Ledezma and Jonathan D. Bray. August 2008.

PEER 2008/04 *Benchmarking of Nonlinear Geotechnical Ground Response Analysis Procedures.* Jonathan P. Stewart, Annie On-Lei Kwok, Yousseff M. A. Hashash, Neven Matasovic, Robert Pyke, Zhiliang Wang, and Zhaohui Yang. August 2008.

PEER 2008/03 *Guidelines for Nonlinear Analysis of Bridge Structures in California.* Ady Aviram, Kevin R. Mackie, and Božidar Stojadinović. August 2008.

PEER 2008/02 *Treatment of Uncertainties in Seismic-Risk Analysis of Transportation Systems.* Evangelos Stergiou and Anne S. Kiremidjian. July 2008.

PEER 2008/01 *Seismic Performance Objectives for Tall Buildings.* William T. Holmes, Charles Kircher, William Petak, and Nabih Youssef. August 2008.

PEER 2007/12 *An Assessment to Benchmark the Seismic Performance of a Code-Conforming Reinforced Concrete Moment-Frame Building.* Curt Haselton, Christine A. Goulet, Judith Mitrani-Reiser, James L. Beck, Gregory G. Deierlein, Keith A. Porter, Jonathan P. Stewart, and Ertugrul Taciroglu. August 2008.

PEER 2007/11 *Bar Buckling in Reinforced Concrete Bridge Columns.* Wayne A. Brown, Dawn E. Lehman, and John F. Stanton. February 2008.

PEER 2007/10 *Computational Modeling of Progressive Collapse in Reinforced Concrete Frame Structures.* Mohamed M. Talaat and Khalid M. Mosalam. May 2008.

PEER 2007/09 *Integrated Probabilistic Performance-Based Evaluation of Benchmark Reinforced Concrete Bridges.* Kevin R. Mackie, John-Michael Wong, and Božidar Stojadinović. January 2008.

PEER 2007/08 *Assessing Seismic Collapse Safety of Modern Reinforced Concrete Moment-Frame Buildings.* Curt B. Haselton and Gregory G. Deierlein. February 2008.

PEER 2007/07 *Performance Modeling Strategies for Modern Reinforced Concrete Bridge Columns.* Michael P. Berry and Marc O. Eberhard. April 2008.

PEER 2007/06 *Development of Improved Procedures for Seismic Design of Buried and Partially Buried Structures.* Linda Al Atik and Nicholas Sitar. June 2007.

PEER 2007/05 *Uncertainty and Correlation in Seismic Risk Assessment of Transportation Systems.* Renee G. Lee and Anne S. Kiremidjian. July 2007.

PEER 2007/04 *Numerical Models for Analysis and Performance-Based Design of Shallow Foundations Subjected to Seismic Loading.* Sivapalan Gajan, Tara C. Hutchinson, Bruce L. Kutter, Prishati Raychowdhury, José A. Ugalde, and Jonathan P. Stewart. May 2008.

PEER 2007/03 *Beam-Column Element Model Calibrated for Predicting Flexural Response Leading to Global Collapse of RC Frame Buildings.* Curt B. Haselton, Abbie B. Liel, Sarah Taylor Lange, and Gregory G. Deierlein. May 2008.

PEER 2007/02 *Campbell-Bozorgnia NGA Ground Motion Relations for the Geometric Mean Horizontal Component of Peak and Spectral Ground Motion Parameters.* Kenneth W. Campbell and Yousef Bozorgnia. May 2007.

PEER 2007/01 *Boore-Atkinson NGA Ground Motion Relations for the Geometric Mean Horizontal Component of Peak and Spectral Ground Motion Parameters.* David M. Boore and Gail M. Atkinson. May. May 2007.

PEER 2006/12 *Societal Implications of Performance-Based Earthquake Engineering.* Peter J. May. May 2007.

PEER 2006/11 *Probabilistic Seismic Demand Analysis Using Advanced Ground Motion Intensity Measures, Attenuation Relationships, and Near-Fault Effects.* Polsak Tothong and C. Allin Cornell. March 2007.

PEER 2006/10 *Application of the PEER PBEE Methodology to the I-880 Viaduct.* Sashi Kunnath. February 2007.

PEER 2006/09 *Quantifying Economic Losses from Travel Forgone Following a Large Metropolitan Earthquake.* James Moore, Sungbin Cho, Yue Yue Fan, and Stuart Werner. November 2006.

PEER 2006/08 *Vector-Valued Ground Motion Intensity Measures for Probabilistic Seismic Demand Analysis*. Jack W. Baker and C. Allin Cornell. October 2006.

PEER 2006/07 *Analytical Modeling of Reinforced Concrete Walls for Predicting Flexural and Coupled–Shear-Flexural Responses*. Kutay Orakcal, Leonardo M. Massone, and John W. Wallace. October 2006.

PEER 2006/06 *Nonlinear Analysis of a Soil-Drilled Pier System under Static and Dynamic Axial Loading.* Gang Wang and Nicholas Sitar. November 2006.

PEER 2006/05 *Advanced Seismic Assessment Guidelines.* Paolo Bazzurro, C. Allin Cornell, Charles Menun, Maziar Motahari, and Nicolas Luco. September 2006.

PEER 2006/04 *Probabilistic Seismic Evaluation of Reinforced Concrete Structural Components and Systems.* Tae Hyung Lee and Khalid M. Mosalam. August 2006.

PEER 2006/03 *Performance of Lifelines Subjected to Lateral Spreading.* Scott A. Ashford and Teerawut Juirnarongrit. July 2006.

PEER 2006/02 *Pacific Earthquake Engineering Research Center Highway Demonstration Project.* Anne Kiremidjian, James Moore, Yue Yue Fan, Nesrin Basoz, Ozgur Yazali, and Meredith Williams. April 2006.

PEER 2006/01 *Bracing Berkeley. A Guide to Seismic Safety on the UC Berkeley Campus.* Mary C. Comerio, Stephen Tobriner, and Ariane Fehrenkamp. January 2006.

PEER 2005/16 *Seismic Response and Reliability of Electrical Substation Equipment and Systems.* Junho Song, Armen Der Kiureghian, and Jerome L. Sackman. April 2006.

PEER 2005/15 *CPT-Based Probabilistic Assessment of Seismic Soil Liquefaction Initiation.* R. E. S. Moss, R. B. Seed, R. E. Kayen, J. P. Stewart, and A. Der Kiureghian. April 2006.

PEER 2005/14 *Workshop on Modeling of Nonlinear Cyclic Load-Deformation Behavior of Shallow Foundations.* Bruce L. Kutter, Geoffrey Martin, Tara Hutchinson, Chad Harden, Sivapalan Gajan, and Justin Phalen. March 2006.

PEER 2005/13 *Stochastic Characterization and Decision Bases under Time-Dependent Aftershock Risk in Performance-Based Earthquake Engineering.* Gee Liek Yeo and C. Allin Cornell. July 2005.

PEER 2005/12 *PEER Testbed Study on a Laboratory Building: Exercising Seismic Performance Assessment.* Mary C. Comerio, editor. November 2005.

PEER 2005/11 *Van Nuys Hotel Building Testbed Report: Exercising Seismic Performance Assessment.* Helmut Krawinkler, editor. October 2005.

PEER 2005/10 *First NEES/E-Defense Workshop on Collapse Simulation of Reinforced Concrete Building Structures.* September 2005.

PEER 2005/09 *Test Applications of Advanced Seismic Assessment Guidelines.* Joe Maffei, Karl Telleen, Danya Mohr, William Holmes, and Yuki Nakayama. August 2006.

PEER 2005/08 *Damage Accumulation in Lightly Confined Reinforced Concrete Bridge Columns.* R. Tyler Ranf, Jared M. Nelson, Zach Price, Marc O. Eberhard, and John F. Stanton. April 2006.

PEER 2005/07 *Experimental and Analytical Studies on the Seismic Response of Freestanding and Anchored Laboratory Equipment.* Dimitrios Konstantinidis and Nicos Makris. January 2005.

PEER 2005/06 *Global Collapse of Frame Structures under Seismic Excitations*. Luis F. Ibarra and Helmut Krawinkler. September 2005.

PEER 2005//05 *Performance Characterization of Bench- and Shelf-Mounted Equipment.* Samit Ray Chaudhuri and Tara C. Hutchinson. May 2006.

PEER 2005/04 *Numerical Modeling of the Nonlinear Cyclic Response of Shallow Foundations.* Chad Harden, Tara Hutchinson, Geoffrey R. Martin, and Bruce L. Kutter. August 2005.

PEER 2005/03 *A Taxonomy of Building Components for Performance-Based Earthquake Engineering.* Keith A. Porter. September 2005.

PEER 2005/02 *Fragility Basis for California Highway Overpass Bridge Seismic Decision Making.* Kevin R. Mackie and Božidar Stojadinović. June 2005.

PEER 2005/01 *Empirical Characterization of Site Conditions on Strong Ground Motion.* Jonathan P. Stewart, Yoojoong Choi, and Robert W. Graves. June 2005.

PEER 2004/09 *Electrical Substation Equipment Interaction: Experimental Rigid Conductor Studies.* Christopher Stearns and André Filiatrault. February 2005.

PEER 2004/08 *Seismic Qualification and Fragility Testing of Line Break 550-kV Disconnect Switches.* Shakhzod M. Takhirov, Gregory L. Fenves, and Eric Fujisaki. January 2005.

PEER 2004/07 *Ground Motions for Earthquake Simulator Qualification of Electrical Substation Equipment.* Shakhzod M. Takhirov, Gregory L. Fenves, Eric Fujisaki, and Don Clyde. January 2005.

PEER 2004/06 *Performance-Based Regulation and Regulatory Regimes.* Peter J. May and Chris Koski. September 2004.

PEER 2004/05 *Performance-Based Seismic Design Concepts and Implementation: Proceedings of an International Workshop.* Peter Fajfar and Helmut Krawinkler, editors. September 2004.

PEER 2004/04 *Seismic Performance of an Instrumented Tilt-up Wall Building.* James C. Anderson and Vitelmo V. Bertero. July 2004.

PEER 2004/03 *Evaluation and Application of Concrete Tilt-up Assessment Methodologies.* Timothy Graf and James O. Malley. October 2004.

PEER 2004/02 *Analytical Investigations of New Methods for Reducing Residual Displacements of Reinforced Concrete Bridge Columns.* Junichi Sakai and Stephen A. Mahin. August 2004.

PEER 2004/01 *Seismic Performance of Masonry Buildings and Design Implications.* Kerri Anne Taeko Tokoro, James C. Anderson, and Vitelmo V. Bertero. February 2004.

PEER 2003/18 *Performance Models for Flexural Damage in Reinforced Concrete Columns.* Michael Berry and Marc Eberhard. August 2003.

PEER 2003/17 *Predicting Earthquake Damage in Older Reinforced Concrete Beam-Column Joints.* Catherine Pagni and Laura Lowes. October 2004.

PEER 2003/16 *Seismic Demands for Performance-Based Design of Bridges.* Kevin Mackie and Božidar Stojadinović. August 2003.

PEER 2003/15 *Seismic Demands for Nondeteriorating Frame Structures and Their Dependence on Ground Motions.* Ricardo Antonio Medina and Helmut Krawinkler. May 2004.

PEER 2003/14 *Finite Element Reliability and Sensitivity Methods for Performance-Based Earthquake Engineering.* Terje Haukaas and Armen Der Kiureghian. April 2004.

PEER 2003/13 *Effects of Connection Hysteretic Degradation on the Seismic Behavior of Steel Moment-Resisting Frames.* Janise E. Rodgers and Stephen A. Mahin. March 2004.

PEER 2003/12 *Implementation Manual for the Seismic Protection of Laboratory Contents: Format and Case Studies.* William T. Holmes and Mary C. Comerio. October 2003.

PEER 2003/11 *Fifth U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures.* February 2004.

PEER 2003/10 *A Beam-Column Joint Model for Simulating the Earthquake Response of Reinforced Concrete Frames*. Laura N. Lowes, Nilanjan Mitra, and Arash Altoontash. February 2004.

PEER 2003/09 *Sequencing Repairs after an Earthquake: An Economic Approach.* Marco Casari and Simon J. Wilkie. April 2004.

PEER 2003/08 *A Technical Framework for Probability-Based Demand and Capacity Factor Design (DCFD) Seismic Formats*. Fatemeh Jalayer and C. Allin Cornell. November 2003.

PEER 2003/07 *Uncertainty Specification and Propagation for Loss Estimation Using FOSM Methods.* Jack W. Baker and C. Allin Cornell. September 2003.

PEER 2003/06 *Performance of Circular Reinforced Concrete Bridge Columns under Bidirectional Earthquake Loading*. Mahmoud M. Hachem, Stephen A. Mahin, and Jack P. Moehle. February 2003.

PEER 2003/05 *Response Assessment for Building-Specific Loss Estimation.* Eduardo Miranda and Shahram Taghavi. September 2003.

PEER 2003/04 *Experimental Assessment of Columns with Short Lap Splices Subjected to Cyclic Loads*. Murat Melek, John W. Wallace, and Joel Conte. April 2003.

PEER 2003/03 *Probabilistic Response Assessment for Building-Specific Loss Estimation.* Eduardo Miranda and Hesameddin Aslani. September 2003.

PEER 2003/02 *Software Framework for Collaborative Development of Nonlinear Dynamic Analysis Program*. Jun Peng and Kincho H. Law. September 2003.

PEER 2003/01 *Shake Table Tests and Analytical Studies on the Gravity Load Collapse of Reinforced Concrete Frames.* Kenneth John Elwood and Jack P. Moehle. November 2003.

PEER 2002/24 *Performance of Beam to Column Bridge Joints Subjected to a Large Velocity Pulse.* Natalie Gibson, André Filiatrault, and Scott A. Ashford. April 2002.

PEER 2002/23 *Effects of Large Velocity Pulses on Reinforced Concrete Bridge Columns.* Greg L. Orozco and Scott A. Ashford. April 2002.

PEER 2002/22 *Characterization of Large Velocity Pulses for Laboratory Testing.* Kenneth E. Cox and Scott A. Ashford. April 2002.

PEER 2002/21 *Fourth U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures*. December 2002.

PEER 2002/20 *Barriers to Adoption and Implementation of PBEE Innovations.* Peter J. May. August 2002.

PEER 2002/19 *Economic-Engineered Integrated Models for Earthquakes: Socioeconomic Impacts.* Peter Gordon, James E. Moore II, and Harry W. Richardson. July 2002.

PEER 2002/18 *Assessment of Reinforced Concrete Building Exterior Joints with Substandard Details.* Chris P. Pantelides, Jon Hansen, Justin Nadauld, and Lawrence D. Reaveley. May 2002.

PEER 2002/17 *Structural Characterization and Seismic Response Analysis of a Highway Overcrossing Equipped with Elastomeric Bearings and Fluid Dampers: A Case Study.* Nicos Makris and Jian Zhang. November 2002.

PEER 2002/16 *Estimation of Uncertainty in Geotechnical Properties for Performance-Based Earthquake Engineering.* Allen L. Jones, Steven L. Kramer, and Pedro Arduino. December 2002.

PEER 2002/15 *Seismic Behavior of Bridge Columns Subjected to Various Loading Patterns.* Asadollah Esmaeily-Gh. and Yan Xiao. December 2002.

PEER 2002/14 *Inelastic Seismic Response of Extended Pile Shaft Supported Bridge Structures.* T.C. Hutchinson, R.W. Boulanger, Y.H. Chai, and I.M. Idriss. December 2002.

PEER 2002/13 *Probabilistic Models and Fragility Estimates for Bridge Components and Systems.* Paolo Gardoni, Armen Der Kiureghian, and Khalid M. Mosalam. June 2002.

PEER 2002/12 *Effects of Fault Dip and Slip Rake on Near-Source Ground Motions: Why Chi-Chi Was a Relatively Mild M7.6 Earthquake.* Brad T. Aagaard, John F. Hall, and Thomas H. Heaton. December 2002.

PEER 2002/11 *Analytical and Experimental Study of Fiber-Reinforced Strip Isolators*. James M. Kelly and Shakhzod M. Takhirov. September 2002.

PEER 2002/10 *Centrifuge Modeling of Settlement and Lateral Spreading with Comparisons to Numerical Analyses***.** Sivapalan Gajan and Bruce L. Kutter. January 2003.

PEER 2002/09 *Documentation and Analysis of Field Case Histories of Seismic Compression during the 1994 Northridge, California, Earthquake.* Jonathan P. Stewart, Patrick M. Smith, Daniel H. Whang, and Jonathan D. Bray. October 2002.

PEER 2002/08 *Component Testing, Stability Analysis and Characterization of Buckling-Restrained Unbonded Braces^{TM}.* Cameron Black, Nicos Makris, and Ian Aiken. September 2002.

PEER 2002/07 *Seismic Performance of Pile-Wharf Connections.* Charles W. Roeder, Robert Graff, Jennifer Soderstrom, and Jun Han Yoo. December 2001.

PEER 2002/06 *The Use of Benefit-Cost Analysis for Evaluation of Performance-Based Earthquake Engineering Decisions*. Richard O. Zerbe and Anthony Falit-Baiamonte. September 2001.

PEER 2002/05 *Guidelines, Specifications, and Seismic Performance Characterization of Nonstructural Building Components and Equipment*. André Filiatrault, Constantin Christopoulos, and Christopher Stearns. September 2001.

PEER 2002/04 *Consortium of Organizations for Strong-Motion Observation Systems and the Pacific Earthquake Engineering Research Center Lifelines Program: Invited Workshop on Archiving and Web Dissemination of Geotechnical Data, 4–5 October 2001*. September 2002.

PEER 2002/03 *Investigation of Sensitivity of Building Loss Estimates to Major Uncertain Variables for the Van Nuys Testbed.* Keith A. Porter, James L. Beck, and Rustem V. Shaikhutdinov. August 2002.

PEER 2002/02 *The Third U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures*. July 2002.

PEER 2002/01 *Nonstructural Loss Estimation: The UC Berkeley Case Study.* Mary C. Comerio and John C. Stallmeyer. December 2001.

PEER 2001/16 *Statistics of SDF-System Estimate of Roof Displacement for Pushover Analysis of Buildings.* Anil K. Chopra, Rakesh K. Goel, and Chatpan Chintanapakdee. December 2001.

PEER 2001/15 *Damage to Bridges during the 2001 Nisqually Earthquake.* R. Tyler Ranf, Marc O. Eberhard, and Michael P. Berry. November 2001.

PEER 2001/14 *Rocking Response of Equipment Anchored to a Base Foundation.* Nicos Makris and Cameron J. Black. September 2001.

PEER 2001/13 *Modeling Soil Liquefaction Hazards for Performance-Based Earthquake Engineering.* Steven L. Kramer and Ahmed-W. Elgamal. February 2001.

PEER 2001/12 *Development of Geotechnical Capabilities in OpenSees*. Boris Jeremić. September 2001.

PEER 2001/11 *Analytical and Experimental Study of Fiber-Reinforced Elastomeric Isolators*. James M. Kelly and Shakhzod M. Takhirov. September 2001.

PEER 2001/10 *Amplification Factors for Spectral Acceleration in Active Regions.* Jonathan P. Stewart, Andrew H. Liu, Yoojoong Choi, and Mehmet B. Baturay. December 2001.

PEER 2001/09 *Ground Motion Evaluation Procedures for Performance-Based Design.* Jonathan P. Stewart, Shyh-Jeng Chiou, Jonathan D. Bray, Robert W. Graves, Paul G. Somerville, and Norman A. Abrahamson. September 2001.

PEER 2001/08 *Experimental and Computational Evaluation of Reinforced Concrete Bridge Beam-Column Connections for Seismic Performance.* Clay J. Naito, Jack P. Moehle, and Khalid M. Mosalam. November 2001.

PEER 2001/07 *The Rocking Spectrum and the Shortcomings of Design Guidelines.* Nicos Makris and Dimitrios Konstantinidis. August 2001.

PEER 2001/06 *Development of an Electrical Substation Equipment Performance Database for Evaluation of Equipment Fragilities*. Thalia Agnanos. April 1999.

PEER 2001/05 *Stiffness Analysis of Fiber-Reinforced Elastomeric Isolators.* Hsiang-Chuan Tsai and James M. Kelly. May 2001.

PEER 2001/04 *Organizational and Societal Considerations for Performance-Based Earthquake Engineering.* Peter J. May. April 2001.

PEER 2001/03 *A Modal Pushover Analysis Procedure to Estimate Seismic Demands for Buildings: Theory and Preliminary Evaluation.* Anil K. Chopra and Rakesh K. Goel. January 2001.

PEER 2001/02 *Seismic Response Analysis of Highway Overcrossings Including Soil-Structure Interaction.* Jian Zhang and Nicos Makris. March 2001.

PEER 2001/01 *Experimental Study of Large Seismic Steel Beam-to-Column Connections.* Egor P. Popov and Shakhzod M. Takhirov. November 2000.

PEER 2000/10 *The Second U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures.* March 2000.

PEER 2000/09 *Structural Engineering Reconnaissance of the August 17, 1999 Earthquake: Kocaeli (Izmit), Turkey.* Halil Sezen, Kenneth J. Elwood, Andrew S. Whittaker, Khalid Mosalam, John J. Wallace, and John F. Stanton. December 2000.

PEER 2000/08 *Behavior of Reinforced Concrete Bridge Columns Having Varying Aspect Ratios and Varying Lengths of Confinement.* Anthony J. Calderone, Dawn E. Lehman, and Jack P. Moehle. January 2001.

PEER 2000/07 *Cover-Plate and Flange-Plate Reinforced Steel Moment-Resisting Connections.* Taejin Kim, Andrew S. Whittaker, Amir S. Gilani, Vitelmo V. Bertero, and Shakhzod M. Takhirov. September 2000.

PEER 2000/06 *Seismic Evaluation and Analysis of 230-kV Disconnect Switches.* Amir S. J. Gilani, Andrew S. Whittaker, Gregory L. Fenves, Chun-Hao Chen, Henry Ho, and Eric Fujisaki. July 2000.

PEER 2000/05 *Performance-Based Evaluation of Exterior Reinforced Concrete Building Joints for Seismic Excitation.* Chandra Clyde, Chris P. Pantelides, and Lawrence D. Reaveley. July 2000.

PEER 2000/04 *An Evaluation of Seismic Energy Demand: An Attenuation Approach.* Chung-Che Chou and Chia-Ming Uang. July 1999.

PEER 2000/03 *Framing Earthquake Retrofitting Decisions: The Case of Hillside Homes in Los Angeles*. Detlof von Winterfeldt, Nels Roselund, and Alicia Kitsuse. March 2000.

PEER 2000/02 *U.S.-Japan Workshop on the Effects of Near-Field Earthquake Shaking.* Andrew Whittaker, ed. July 2000.

PEER 2000/01 *Further Studies on Seismic Interaction in Interconnected Electrical Substation Equipment.* Armen Der Kiureghian, Kee-Jeung Hong, and Jerome L. Sackman. November 1999.

PEER 1999/14 *Seismic Evaluation and Retrofit of 230-kV Porcelain Transformer Bushings*. Amir S. Gilani, Andrew S. Whittaker, Gregory L. Fenves, and Eric Fujisaki. December 1999.

PEER 1999/13 *Building Vulnerability Studies: Modeling and Evaluation of Tilt-up and Steel Reinforced Concrete Buildings.* John W. Wallace, Jonathan P. Stewart, and Andrew S. Whittaker, editors. December 1999.

PEER 1999/12 *Rehabilitation of Nonductile RC Frame Building Using Encasement Plates and Energy-Dissipating Devices.* Mehrdad Sasani, Vitelmo V. Bertero, James C. Anderson. December 1999.

PEER 1999/11 *Performance Evaluation Database for Concrete Bridge Components and Systems under Simulated Seismic Loads.* Yael D. Hose and Frieder Seible. November 1999.

PEER 1999/10 *U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures.* December 1999.

PEER 1999/09 *Performance Improvement of Long Period Building Structures Subjected to Severe Pulse-Type Ground Motions*. James C. Anderson, Vitelmo V. Bertero, and Raul Bertero. October 1999.

PEER 1999/08 *Envelopes for Seismic Response Vectors.* Charles Menun and Armen Der Kiureghian. July 1999.

PEER 1999/07 *Documentation of Strengths and Weaknesses of Current Computer Analysis Methods for Seismic Performance of Reinforced Concrete Members.* William F. Cofer. November 1999.

PEER 1999/06 *Rocking Response and Overturning of Anchored Equipment under Seismic Excitations.* Nicos Makris and Jian Zhang. November 1999.

PEER 1999/05 *Seismic Evaluation of 550 kV Porcelain Transformer Bushings.* Amir S. Gilani, Andrew S. Whittaker, Gregory L. Fenves, and Eric Fujisaki. October 1999.

PEER 1999/04 *Adoption and Enforcement of Earthquake Risk-Reduction Measures.* Peter J. May, Raymond J. Burby, T. Jens Feeley, and Robert Wood.

PEER 1999/03 *Task 3 Characterization of Site Response General Site Categories*. Adrian Rodriguez-Marek, Jonathan D. Bray, and Norman Abrahamson. February 1999.

PEER 1999/02 *Capacity-Demand-Diagram Methods for Estimating Seismic Deformation of Inelastic Structures: SDF Systems*. Anil K. Chopra and Rakesh Goel. April 1999.

PEER 1999/01 *Interaction in Interconnected Electrical Substation Equipment Subjected to Earthquake Ground Motions.* Armen Der Kiureghian, Jerome L. Sackman, and Kee-Jeung Hong. February 1999.

PEER 1998/08 *Behavior and Failure Analysis of a Multiple-Frame Highway Bridge in the 1994 Northridge Earthquake.* Gregory L. Fenves and Michael Ellery. December 1998.

PEER 1998/07 *Empirical Evaluation of Inertial Soil-Structure Interaction Effects.* Jonathan P. Stewart, Raymond B. Seed, and Gregory L. Fenves. November 1998.

PEER 1998/06 *Effect of Damping Mechanisms on the Response of Seismic Isolated Structures.* Nicos Makris and Shih-Po Chang. November 1998.

PEER 1998/05 *Rocking Response and Overturning of Equipment under Horizontal Pulse-Type Motions.* Nicos Makris and Yiannis Roussos. October 1998.

PEER 1998/04 *Pacific Earthquake Engineering Research Invitational Workshop Proceedings, May 14–15, 1998: Defining the Links between Planning, Policy Analysis, Economics and Earthquake Engineering.* Mary Comerio and Peter Gordon. September 1998.

PEER 1998/03 *Repair/Upgrade Procedures for Welded Beam to Column Connections.* James C. Anderson and Xiaojing Duan. May 1998.

PEER 1998/02 *Seismic Evaluation of 196 kV Porcelain Transformer Bushings.* Amir S. Gilani, Juan W. Chavez, Gregory L. Fenves, and Andrew S. Whittaker. May 1998.

PEER 1998/01 *Seismic Performance of Well-Confined Concrete Bridge Columns.* Dawn E. Lehman and Jack P. Moehle. December 2000.

ONLINE REPORTS

The following PEER reports are available by Internet only at http://peer.berkeley.edu/publications/peer_reports.html

PEER 2011/102 *Ground-motion prediction equations 1964 - 2010.* John Douglas. April 2011.

PEER 2011/101 *Report of the Eighth Planning Meeting of NEES/E-Defense Collaborative Research on Earthquake Engineering.* Convened by the Hyogo Earthquake Engineering Research Center (NIED), NEES Consortium, Inc. February 2011.

PEER 2010/111 *Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings.* Task 7 Report for the Tall Buildings Initiative - Published jointly by the Applied Technology Council. October 2010.

PEER 2010/110 *Seismic Performance Assessment and Probabilistic Repair Cost Analysis of Precast Concrete Cladding Systems for Multistory Buildlings.* Jeffrey P. Hunt and Božidar Stojadinovic. November 2010.

PEER 2010/109 *Report of the Seventh Joint Planning Meeting of NEES/E-Defense Collaboration on Earthquake Engineering. Held at the E-Defense, Miki, and Shin-Kobe, Japan, September 18–19, 2009.* August 2010.

PEER 2010/108 *Probabilistic Tsunami Hazard in California.* Hong Kie Thio, Paul Somerville, and Jascha Polet, preparers. October 2010.

PEER 2010/107 *Performance and Reliability of Exposed Column Base Plate Connections for Steel Moment-Resisting Frames.* Ady Aviram, Božidar Stojadinovic, and Armen Der Kiureghian. August 2010.

PEER 2010/106 *Verification of Probabilistic Seismic Hazard Analysis Computer Programs.* Patricia Thomas, Ivan Wong, and Norman Abrahamson. May 2010.

PEER 2010/105 *Structural Engineering Reconnaissance of the April 6, 2009, Abruzzo, Italy, Earthquake, and Lessons Learned.* M. Selim Günay and Khalid M. Mosalam. April 2010.

PEER 2010/104 *Simulating the Inelastic Seismic Behavior of Steel Braced Frames, Including the Effects of Low-Cycle Fatigue.* Yuli Huang and Stephen A. Mahin. April 2010.

PEER 2010/103 *Post-Earthquake Traffic Capacity of Modern Bridges in California.* Vesna Terzic and Božidar Stojadinović. March 2010.

PEER 2010/102 *Analysis of Cumulative Absolute Velocity (CAV) and JMA Instrumental Seismic Intensity (I_{JMA}) Using the PEER–NGA Strong Motion Database.* Kenneth W. Campbell and Yousef Bozorgnia. February 2010.

PEER 2010/101 *Rocking Response of Bridges on Shallow Foundations.* Jose A. Ugalde, Bruce L. Kutter, and Boris Jeremic. April 2010.

PEER 2009/109 *Simulation and Performance-Based Earthquake Engineering Assessment of Self-Centering Post-Tensioned Concrete Bridge Systems.* Won K. Lee and Sarah L. Billington. December 2009.

PEER 2009/108 *PEER Lifelines Geotechnical Virtual Data Center.* J. Carl Stepp, Daniel J. Ponti, Loren L. Turner, Jennifer N. Swift, Sean Devlin, Yang Zhu, Jean Benoit, and John Bobbitt. September 2009.

PEER 2009/107 *Experimental and Computational Evaluation of Current and Innovative In-Span Hinge Details in Reinforced Concrete Box-Girder Bridges: Part 2: Post-Test Analysis and Design Recommendations.* Matias A. Hube and Khalid M. Mosalam. December 2009.

PEER 2009/106 *Shear Strength Models of Exterior Beam-Column Joints without Transverse Reinforcement.* Sangjoon Park and Khalid M. Mosalam. November 2009.

PEER 2009/105 *Reduced Uncertainty of Ground Motion Prediction Equations through Bayesian Variance Analysis.* Robb Eric S. Moss. November 2009.

PEER 2009/104 *Advanced Implementation of Hybrid Simulation.* Andreas H. Schellenberg, Stephen A. Mahin, Gregory L. Fenves. November 2009.

PEER 2009/103 *Performance Evaluation of Innovative Steel Braced Frames.* T. Y. Yang, Jack P. Moehle, and Božidar Stojadinovic. August 2009.

PEER 2009/102 *Reinvestigation of Liquefaction and Nonliquefaction Case Histories from the 1976 Tangshan Earthquake.* Robb Eric Moss, Robert E. Kayen, Liyuan Tong, Songyu Liu, Guojun Cai, and Jiaer Wu. August 2009.

PEER 2009/101 *Report of the First Joint Planning Meeting for the Second Phase of NEES/E-Defense Collaborative Research on Earthquake Engineering.* Stephen A. Mahin et al. July 2009.

PEER 2008/104 *Experimental and Analytical Study of the Seismic Performance of Retaining Structures.* Linda Al Atik and Nicholas Sitar. January 2009.

PEER 2008/103 *Experimental and Computational Evaluation of Current and Innovative In-Span Hinge Details in Reinforced Concrete Box-Girder Bridges. Part 1: Experimental Findings and Pre-Test Analysis.* Matias A. Hube and Khalid M. Mosalam. January 2009.

PEER 2008/102 *Modeling of Unreinforced Masonry Infill Walls Considering In-Plane and Out-of-Plane Interaction.* Stephen Kadysiewski and Khalid M. Mosalam. January 2009.

PEER 2008/101 *Seismic Performance Objectives for Tall Buildings.* William T. Holmes, Charles Kircher, William Petak, and Nabih Youssef. August 2008.

PEER 2007/101 *Generalized Hybrid Simulation Framework for Structural Systems Subjected to Seismic Loading.* Tarek Elkhoraibi and Khalid M. Mosalam. July 2007.

PEER 2007/100 *Seismic Evaluation of Reinforced Concrete Buildings Including Effects of Masonry Infill Walls.* Alidad Hashemi and Khalid M. Mosalam. July 2007.

The Pacific Earthquake Engineering Research Center (PEER) is a multi-institutional research and education center with headquarters at the University of California, Berkeley. Investigators from over 20 universities, several consulting companies, and researchers at various state and federal government agencies contribute to research programs focused on performance-based earthquake engineering.

These research programs aim to identify and reduce the risks from major earthquakes to life safety and to the economy by including research in a wide variety of disciplines including structural and geotechnical engineering, geology/seismology, lifelines, transportation, architecture, economics, risk management, and public policy.

PEER is supported by federal, state, local, and regional agencies, together with industry partners.

PEER reports can be ordered at http://peer.berkeley.edu/publications/peer_reports.html or by contacting

Pacific Earthquake Engineering Research Center
University of California, Berkeley
325 Davis Hall, mail code 1792
Berkeley, CA 94720-1792
Tel: 510-642-3437
Fax: 510-642-1655
Email: peer_editor@berkeley.edu

ISSN 1547-0587X