Application of Geophysics to Highway Engineering In Michigan

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Because conventional methods of resistivity interpretation did not consistently yield the desired results, the Michigan State Highway Department developed the Barnes layer method of interpretation. This method is described briefly and compared with others. The seismic method and equipment are also discussed. The resistivity and seismic methods complement each other and, in combination with borings, give a good picture of subsurface conditions.

Surveys may be divided into two main categories, roadway cut sections and borrow pits. Roadway cut section surveys are discussed along with the format of the survey reports and their benefits to the department. Borrow pits are divided into dry and underwater pits, and the peculiarities of surveying each type are covered. Geophysical surveys also assist in solving special problems, as in materials investigation surveys conducted for use in court litigations and land appraisal. Surveys are also made to obtain additional information on buried river valleys, mine caving, and swamps.

•AS ROAD DESIGNS and specifications have become increasingly sophisticated, more demanding uses have been made of natural earth materials. The Michigan State Highway Department recognized the need for more soils information by pioneering the application of the agricultural soils survey to highway engineering.

Although the pedological soil survey yields considerable information, it is limited in depth. Michigan soils, the product of continental glaciation, are complex and often change radically with depth. Therefore, as vertical and horizontal grade requirements for roadway alignment gradually became more rigid, the need became acute for deep, detailed subsurface investigations of specific areas.

MICHIGAN RESISTIVITY PROGRAM

In 1949, the Michigan State Highway Department purchased a Shepard-type earth resistivity apparatus, manufactured by Geophysical Corp. It was soon apparent that a great deal of experimental work would be required to obtain a complete and accurate correlation between interpretation of resistivity readings and actual subsurface conditions. Conventional methods were tried with only partially satisfactory results. In fact, the results of the interpretations based on conventional methods were considerably lacking in the detailed information required to supplement and validate the soil engineers' data. Whereas conventional methods of interpretation often gave good results, it was found that desired information could not always be obtained with reliability. It was evident that a method had to be developed to furnish continuous information for relatively large areas.

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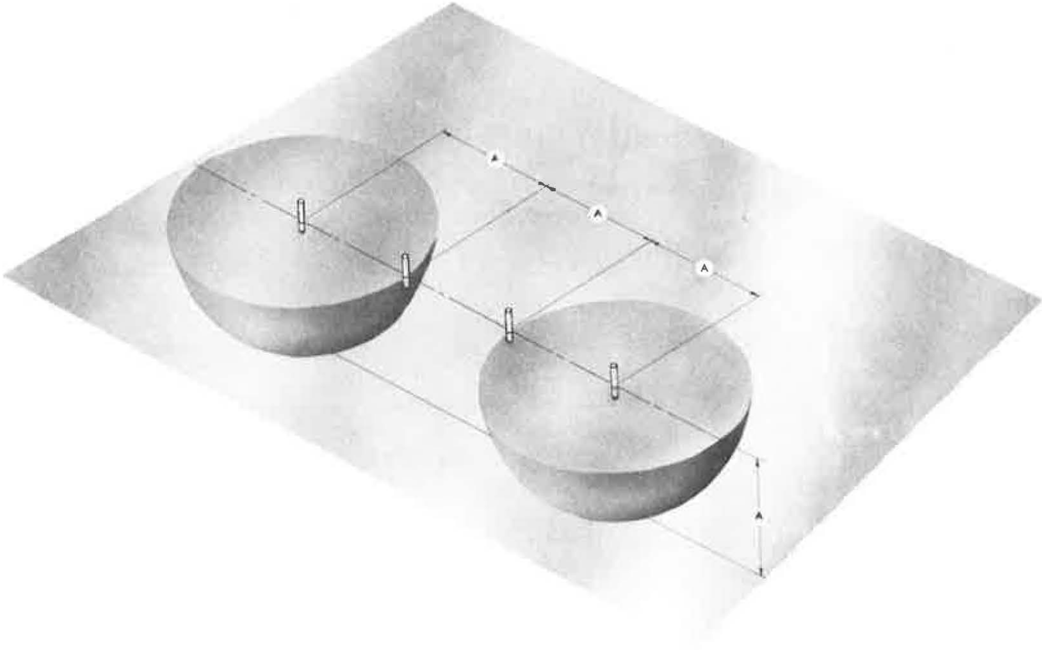


Figure 1. Soil mass measured by "potential bowl" theory.

In 1952, Barnes (1) developed the theory for a new method of resistivity interpretation. Later (2, pp. 81-84) he explained the mechanics of the method, giving additional information on resistivity interpretation based on observations of open-cut sections and borrow pits.

The electrical earth resistivity method of geophysical exploration is based on the premise that different soil and rock types yield different values of average apparent resistivity. The basic Wenner configuration (3) is used, in which four electrodes are driven into the ground along a straight line and equidistant from each other. An electrical current is induced through the outside electrodes and the potential fall is measured across the inside electrodes. By inserting the measured values of amperage, voltage, and electrode spacing into Wenner's formula, the value of average apparent resistivity may be determined as follows:

$$\rho = 191 A \ E/I \tag{1}$$

where

ρ = average apparent resistivity (ohm-cm),
191 = constant for converting feet to centimeters including the factor of π,
A = electrode spacing (ft),
E = potential fall across the inner two electrodes (volts), and
I = current carried through the soil mass as introduced through the outer electrodes (amp).

The actual volume and shape of the measured soil mass is a subject of controversy. However, the "potential bowl" theory (4, pp. 507-508) indicates that it is an oddly shaped solid located between the potential bowls shown in Figure 1. It is believed that the limits between the inner electrodes are sharply defined. The limits normal to a line between the inner electrodes are vague. The lower limit or depth as indicated by Wenner's formula is equal to the electrode spacing A. There is some question (4, p. 509) as to whether the depth being measured is equal to the electrode spacing A or to some factor of A. In the past 12 years, Michigan has conducted surveys totaling

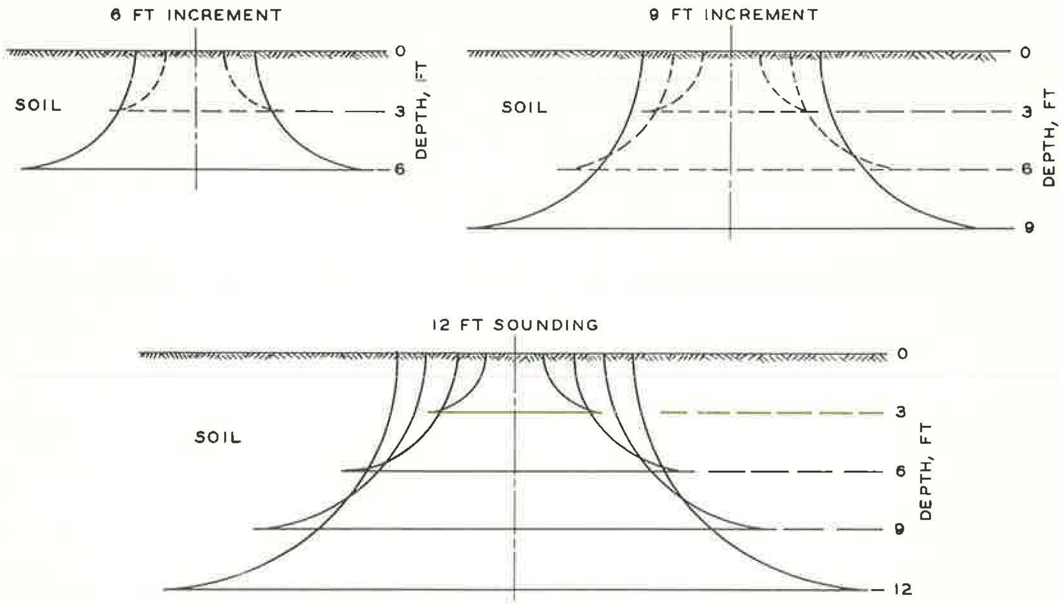


Figure 2. Development of resistivity soundings by increments.

approximately 34,000 resistivity soundings and over 4,000 correlation borings. The results have indicated that the electrode spacing A is equal to the depth A. However, this statement should be qualified by limiting it to depths under 65 ft, using instruments of similar power to Michigan's.

Several types of resistivity soundings can be made, but only one type is discussed, consisting of the Wenner configuration with incremented electrode spacings about a fixed point resulting in an electrical log of the soil from the ground surface to any given depth. Figure 2 indicates that as the increments of electrode spacing increase, the depth and volume of the measured soil mass increase. This has a definite effect on the E/I ratio in Wenner's formula. Assuming a theoretical homogeneous soil mass, equal increments of electrode spacing, and a value of x for the E/I ratio of the first increment, the E/I ratio of the second increment will be x/2, of the third increment will be x/3, and so forth, to x/n. Because all soils are to some degree heterogeneous, variation of the E/I ratio from this hypothetical homogeneous ratio allows resistivity interpretation of different soil and rock types.

Nearly all types of resistivity interpretations are based on some form of average apparent resistivity. Figure 2 shows that the 3-ft increment measures a volume of soil 3 ft in depth. The 6-ft increment measures a volume of soil 6 ft in depth, including the volume previously measured by the 3-ft increment. Each additional increment, therefore, adds an additional volume of soil around and below any previously measured increments. Since most soil changes are vertical rather than horizontal, differences in average apparent resistivity between increments are due to the part of a given increment below the previous increment, rather than around it.

Because of the cumulative nature of the increasing resistivity increments, the effects of a change in soil type with depth decrease in direct proportion to the E/I ratio. The difference between the E/I ratios of the first and second increments (x to x/2) is much greater than the E/I ratios between the eighth and ninth increments (x/8 to x/9)—a difference of 1 to $\frac{1}{2}$ vs a difference of $\frac{1}{8}$ to $\frac{1}{9}$. Thus, a relatively minor change in soil at a shallow depth can produce as great a change in average apparent resistivity as a major change in soil type at a greater depth. This cumulative property of average apparent resistivity tends to mask soil changes with depth and constitutes one of the major problems of interpretation.

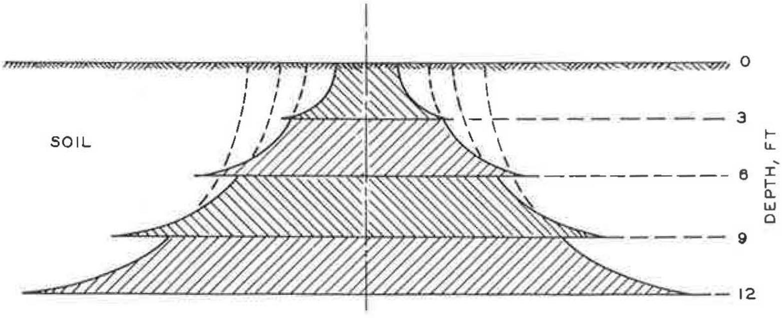


Figure 3. Resistivity of individual layers by increments of depth.

Many unique methods and manipulations of data have been contrived for resistivity interpretation. The Moore cumulative curve (5) consists of a cumulative curve plot of the average apparent resistivity values vs depth. Straight lines are then drawn along the straighter parts of the curve and intersect at inflection points, similar to the seismic time-distance curve. The intersections of these points on the abscissa give the depths of major breaks in soil and rock types. The curve measures the relative rate of change of the average apparent resistivity values for successive increments.

In certain areas characterized by granular soils over clay with high water tables containing electrolytes, the Barnes layer method does not reflect soils changes but is more indicative of the electrolyte concentration. The Moore cumulative curve method, which is sensitive to change of rate independent of the relative resistivity value, works well in this situation.

Most other methods of interpretation consist of families of curves drawn for various situations of two and three layers of high- and low-resistivity materials. Resistivity soundings made in the field are plotted as average apparent resistivity values vs depth. The curves obtained are then matched against the master curves, and subsurface conditions are assumed to equal or nearly to equal the master curve condition. All these methods work to a certain degree but are limited as to the number of layers that can be distinguished and measured.

The Barnes layer method was developed as a probable solution to the masking effects of the average apparent resistivity method of subsurface exploration. The layer method measures the volume of soil added below each previous increment, rather than the average apparent resistivity from the ground surface to the depth of a given increment. Figure 3 contains a 12-ft resistivity sounding showing the relationship between individual layers. Inasmuch as the increments in a resistivity sounding can be likened to resistances in a parallel circuit, it is possible by a manipulation of Ohm's law to compute any unknown conductance when the remaining resistances in the circuit are known.

The layer method works in the following manner. Assuming 3-ft increments, the first increment measures the resistivity of a volume of soil 3 ft in depth and is the resistivity layer value for that increment. The 6-ft increment measuring a volume of soil 6 ft in depth includes that soil mass previously measured by the 3-ft increment plus an additional 3-ft layer of soil. This can be compared with two resistors in a parallel circuit where the conductances of one resistor (the 3-ft increment) and of the entire circuit (the 6-ft increment) are known, and the conductance of the second resistor (the layer conductance between 3 and 6 ft in depth) is unknown. Thus, it is possible to solve for the unknown conductance by the following formula (2, p. 81):

$$\frac{1}{R_n} = \frac{1}{\bar{R}_n} - \frac{1}{\bar{R}_{n-1}} \tag{2}$$

where

$\frac{1}{R_n}$ = layer conductance of a given increment (mho),

$\frac{1}{\bar{R}_n}$ = total conductance between ground surface and bottom of given increment (mho), and

$\frac{1}{\bar{R}_{n-1}}$ = total conductance between ground surface and bottom of increment directly above given increment (mho).

The resistivity layer value for any given increment can then be computed by the modified Wenner's formula,

$$\rho_L = \frac{191\ A_L}{1/R_n} \qquad (3)$$

where

ρ_L = layer resistivity (ohm-cm),

191 = constant for converting feet to centimeters including the factor of π,

A_L = thickness of any given layer or increment (ft), and

$\frac{1}{R_n}$ = layer conductance of any given increment $\underline{n}$ (mho).

Some theoretical objections do exist, such as the effects of warped equipotential surfaces. It has also been said (6) that the Barnes layer method is not intended to yield numerical depths to geologic boundaries and that the layer boundaries have no real significance in terms of actual geologic boundaries. However, in practice, the method works exceptionally well, as is indicated by the comparison of average apparent resistivity values and apparent resistivity layer values for a given sounding in Table 1.

Application and Interpretation of Resistivity

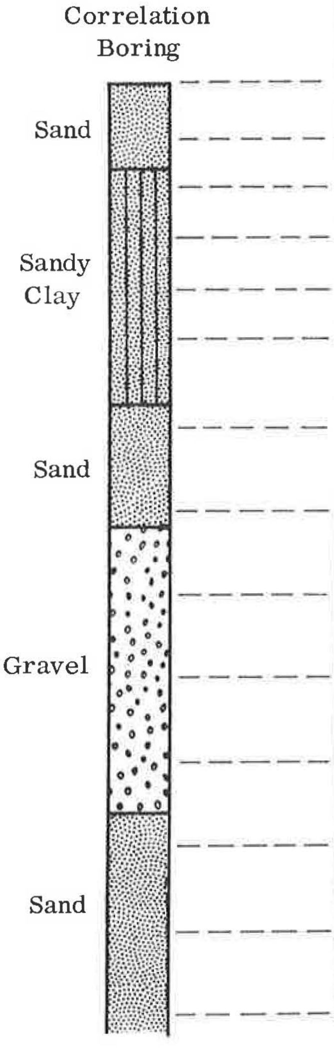
Michigan's standard procedure for resistivity surveys consists of running a series of resistivity soundings at 100-ft intervals along a line called a rho-traverse. A survey may consist of a single rho-traverse, as along a survey centerline in a proposed cut section, or a series of parallel roh-traverses covering a wide area, as in the survey of a proposed borrow area. The geophysical data from a survey are checked and sent to the department's data processing section for reduction by electronic computer, allowing rapid and accurate treatment of a large mass of data. (Without the electronic computer, the preparation and reporting of the large number of geophysical reports over the past several years would not have been possible.) The final use of the survey data is in construction of cross-sections from profile contours (Fig. 4). These are pictorial graphs of the rho-traverses depicting arbitrary resistivity layer values as contours whose depths are obtained by electronic computer and plotted in relation to the actual ground surface. Other pertinent information shown includes stationing, elevations, proposed grade, water table, index correlation boring logs, and laboratory test results.

Resistivity layer values are interpreted by comparing the electrical logs to index correlation borings. It is generally found that the major textural soil classes such as clay and sandy clay, loamy sand, sand, and gravel will fall into definable ranges of resistivity values which are usually constant for a given area. Because the same soil types will yield different range values, and different soil types will yield similar range values under varying environments, correlation borings in each new area are essential.

The resistivity layer range values chosen for the different soil types will rarely coincide exactly with the correlation boring contacts. The relatively large volume

TABLE 1

COMPARISON OF AVERAGE APPARENT RESISTIVITY
WITH BARNES LAYER VALUES



Depth, ft	Rho (ρ) Average, ohm-cm	Rho (ρ) Layer, ohm-cm
3	130,800	130,800
6	80,100	57,700
9	43,600	22,800
12	30,400	16,000
15	25,700	15,800
20	28,000	38,800
25	32,300	82,300
30	37,800	258,800
35	43,900	1,492,200
40	50,200	19,100,000
45	54,200	148,500
50	55,700	75,700
55	57,400	81,800

of the resistivity layers tends to cancel out minor irregularities in the soil, which point information of the boring will include. Also, unless the contact between two resistivity layers falls exactly on the contact between two different soil types, the resulting resistivity layer value will be a combination of the two different soil types. The ideal correlation between resistivity and boring data occurs when the soils contact, as indicated by two or more correlation borings, straddles the profile contour chosen for that particular contact.

When correlation borings are made, representative samples are taken of the granular fractions of the subsoils and are submitted to the Testing Laboratory Division to determine their suitability for use as specification material. In clayey soils, occasional samples are taken to be tested for percent of natural moisture. This aids in proper classification of the material with reference to lacustrine or till origin or a combination which is sometimes difficult to determine. Also, some insight is obtained

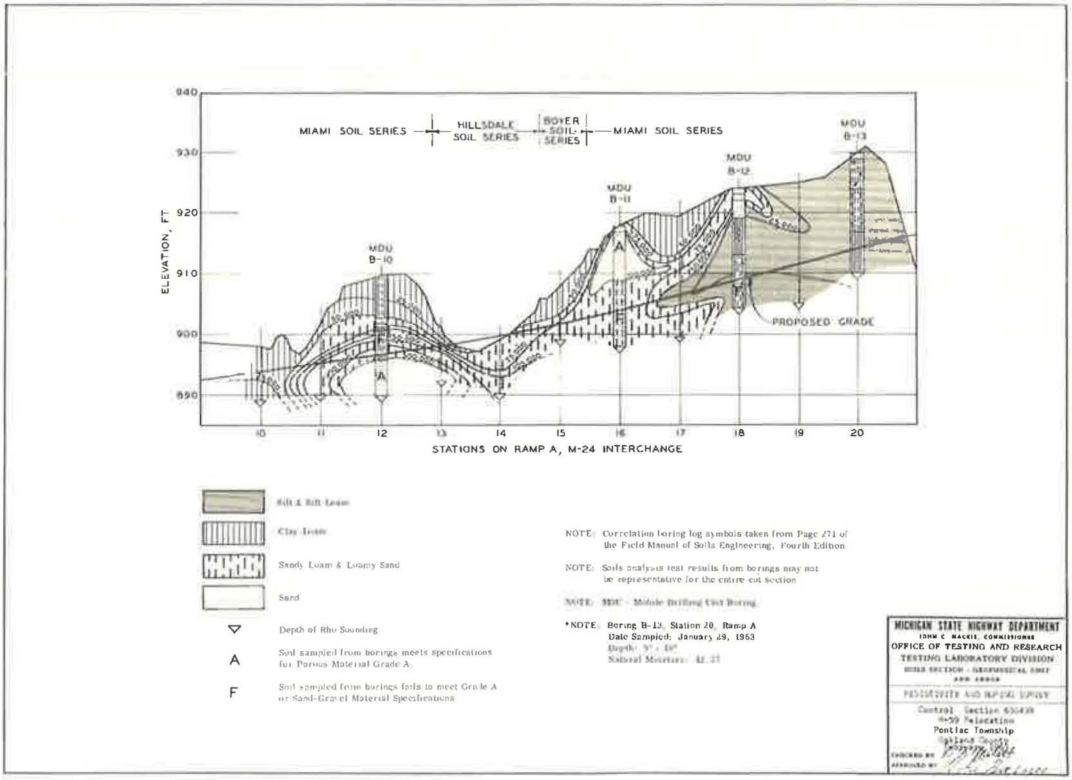


Figure 4. Cross-section from resistivity profile contours.

Figure 5. B-36 mobile drilling unit.

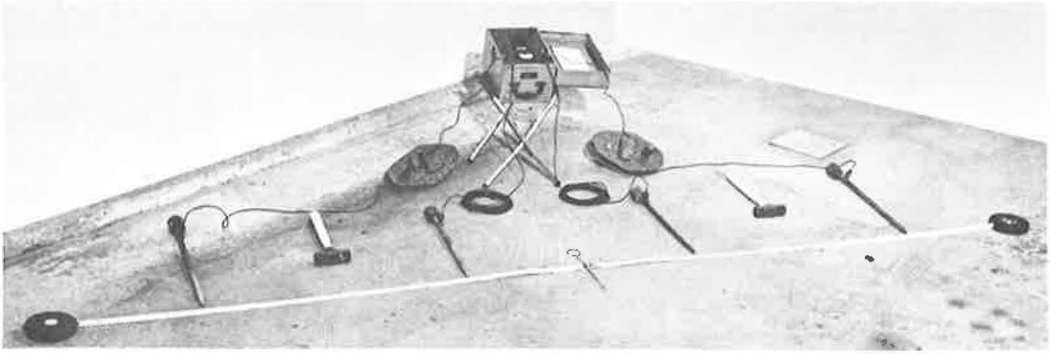


Figure 6. Michimho Model 274-M with accessory equipment.

as to the workability of the material, particularly if the natural moisture can be compared with the optimum moisture as determined by the AASHO T-99 Proctor test.

As previously mentioned, resistivity layer values for the same material will vary with environment. Many factors can influence layer values, the most important being moisture and dissolved electrolytes. In the spring when the major water table recharge takes place and the entire soil mass is thoroughly moist, excellent anomalies exist among the major soil types. As the ground begins to dry in midsummer, the layer values for the more granular soil fractions begin to fluctuate. By fall, when the ground is extremely dry, correlation between sand and gravel often breaks down so that the two cannot always be differentiated with certainty. The finer soil fractions such as loamy sand and silt, when dry, often yield resistivity layer values in the sand ranges. Sometimes the presence of water table will change the range values of a given soil type. These conditions can be quite troublesome, but an awareness of the situation, a knowledge of soils, and accurate correlation borings can usually solve such problems.

Proper location of correlation borings often determines the relative success of a resistivity survey. Ideally, the borings are drilled after cross-sections have been drawn from profile contours. Boring locations can then be selected where typical contacts exist and major structures appear. Usually, because of time and distance limitations, correlation borings are made during the resistivity survey, when boring locations are selected from surface observations. During the course of a year, correlation borings taken for the Michigan State Highway Department with a continuous flight auger will generally average one boring per seven resistivity soundings. The Department uses truck-mounted B-36 and B-52 mobile drilling units (Fig. 5). Manufactured by Mobile Drilling, Inc.

Michigan uses the Michimho Resistivity Instrument Model 274-M, manufactured by Associated Research, Inc. (Fig. 6). This is a geophysical instrument redesigned from an earlier model for improvement of sensitivity and modified specifically to read in "mho's" for use with the Barnes layer method. The instrument (7) consists of a power supply, a current supply circuit, and a measuring circuit. The power supply changes the low dc battery voltage (3 volts) to an alternating current by a 97-cps synchronous vibrator. This voltage is stepped up to 125 volts by the power transformer, which in the current supply circuit is connected in series with a calibrated potentiometer. Because the meter current is commutated by the 97-cps vibrator, the instrument is unaffected by stray 60-cycle power line or ground currents. A blocking capacitor in the potential circuit also prevents stray dc ground voltages from affecting the readings.

MICHIGAN SEISMIC PROGRAM

Earth resistivity is not an end in itself, but merely another tool available to the engineer and geologist for subsurface exploration. Like any tool, it has limitations. Resistivity measures electrical properties of soil and rock. If certain different soil and rock types (for example, clayey Wisconsin Age Drift overlying clayey Pre-

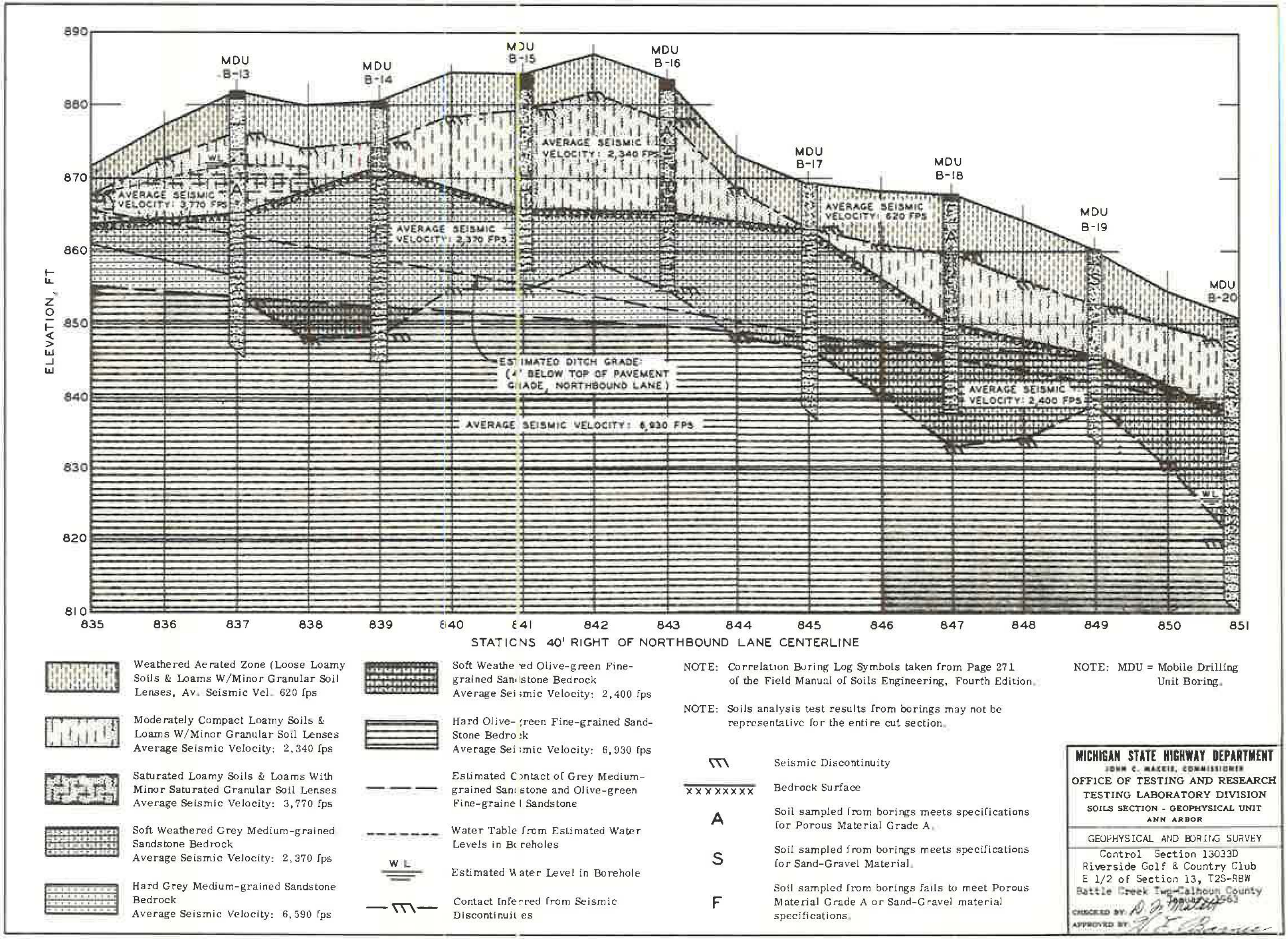


Figure 7. Cross-section from seismic discontinuities and borings.

Wisconsin Age Drift, or sand overlying sandstone) yield similar resistivity values, then no method of resistivity interpretation can differentiate them. The resistivity method would not indicate the contacts between these layers because each pair of layers has similar electrical properties. These different materials do have dissimilar elastic properties, however, and could be differentiated by the seismic method of subsurface exploration. Therefore, the seismic method in many cases complements the earth resistivity method. Its addition to a geophysical survey program considerably broadens the comprehensiveness of collection and evaluation of subsurface data for engineering purposes.

In addition to complementing earth resistivity, the seismic method collects facts that are in themselves unique and valuable, such as velocity data on soil and rock. Proper collection and evaluation of this information gives valuable insight as to the workability of the different materials. Figure 7 shows a cross-section from seismic discontinuities and borings, outlining various rock layers in sandstone bedrock on the basis of seismic velocity. This information can be used to establish separate pay items for special excavation methods for given soil and rock zones. Under proper control the seismic velocities in a given rock bed also can be used to evaluate that bed as a structural unit. Velocity anomalies in the rock bed may indicate weaker zones and may outline areas for additional core drill investigation and possible grouting.

There are two types of seismic surveys presently used in exploration work: reflection and refraction methods. They are similar in that both are based on the detection and measurement of artifically induced seismic waves, but are dissimilar with respect to the specific types of seismic wave detected and measured. The reflection method is based on the detection and measurement of seismic waves which travel downward through the earth and are reflected back to the surface by the interfaces between various layers of soil and rock. This occurs in a manner exactly analogous to the reflection of light rays by a mirror. The refraction method is based on the ability of layered earth materials to bend or refract seismic waves passing through them in such a way that some of the wave energy is returned to the earth's surface after penetrating the various strata. This phenomenon permits measurement of the amount of time necessary for the passage of these waves through various layers of soil or rock.

The velocity of propagation of seismic energy waves throughout a solid depends on the elastic properties of the particular material. The elasticity of earth materials varies over a considerable range. The velocities of seismic waves in earth materials increase in proportion to increases in the elasticities of these materials. An increase in the density of soil is generally accompanied by an increase in seismic wave velocities. If the energy transmitting material is homogeneous, the velocity of the seismic waves will be constant and the advancing wave front will assume a spherical form. The waves will be bent or refracted if they pass into a body of earth material which has a differing elasticity, density, or hardness. The mathematical relationships involved in seismic interpretations have been well covered in a variety of publication and textbooks (8) and will not be repeated here.

Seismic Equipment

The Michigan State Highway Department entered the field of refraction seismology in 1958 with the purchase of a Model MD-1 engineering seismograph manufactured by Geophysical Specialities, Inc. (Fig. 8). This instrument is essentially a very accurate electronic counter connected to a seismic detector and to a sledge hammer. An elastic wave is generated into the ground by striking the sledge hammer on a steel plate lying on the ground. At the instant the sledge hammer strikes the steel plate, a momentary contact switch on the hammer closes and starts the counter on the seismograph. The counter is turned off when the elastic wave reaches the seismic detector and activates it. The time it takes the elastic wave to travel from the impact point to the counter can be read to the nearest 1/4 millisecond by a series of timing lights on the counter. A seismic sounding is made by selecting a series of measured impact points along a line away from the instrument. The depths measured are generally one-half to one-fifth of the horizontal spread. By graphing the time-distance values obtained, the velocities and thicknesses of the various soil and rock layers can be computed.

Figure 8. Geologist operating Model MD-1 engineering seismograph.

The seismic method was found to have considerable merit. In some cases, not only could bedrock be outlined, but also various zones within the rock could be delineated and classified with reference to possible methods of excavation. Different density zones in clayey glacial drift could be outlined accurately, as shown in Figure 9. The 7,491-fps zone at the bottom of the profile is Pre-Wisconsin clayey drift which required ripping for removal. Under certain conditions, the top of a saturated zone could be indicated.

The success of the single-trace seismograph led to the purchase, in 1961, of an Electro-Technical Labs 12-trace seismograph, which greatly extended seismic capabilities. The instrument is truck-mounted (Fig. 10), and uses explosives to generate the elastic wave. The explosives include Hercules Vibrocaps (SR, No. 6), Primacord, and DuPont Nitramon S and Nitramon S Primers. The blasting caps and Nitramon S Primers require careful handling and storage in special powder magazines. The Primacord and Nitramon S require no special handling or storage in magazines, but should be treated with the respect due such materials. The DuPont Nitramon S and Nitramon S Primers come in 2-in. diameter, 1-lb cans that can be screwed together to any length and size charge desired. They are lowered in an auger hole and detonated by either Primacord or an electric blasting cap inserted in a hole in the primer charge and held in place by a special plastic shield. Figure 11 shows a seismic charge ready for placing in a shot hole.

The Electro-Tech seismograph consists of a PRA2-12 amplifier which allows adjustments of gain, output level, and filter to be made separately on each of the 12 EVS-4B refraction detectors (geophones). Geophone cables of 50- and 20-ft takeout spacing were purchased. The signals from the amplifiers are fed into an ER-64 recording oscillograph and are recorded on photographic paper. A general view inside the seismic truck is shown in Figure 12.

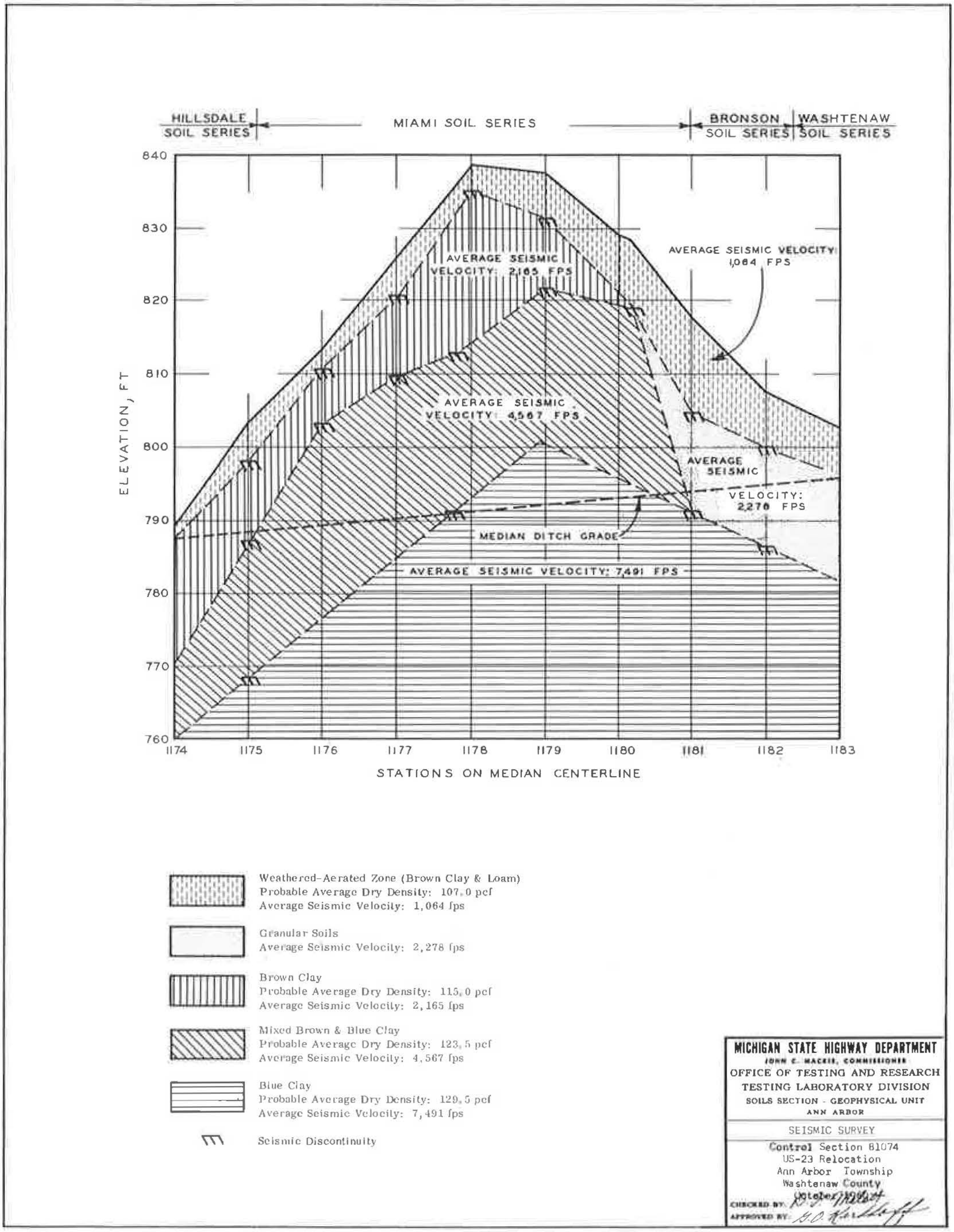


Figure 9. Cross-section from seismic discontinuities showing zones of increasing density and seismic velocity in clayey glacial drift.

Figure 10. Seismic truck.

Figure 11. Explosives handler with seismic charge.

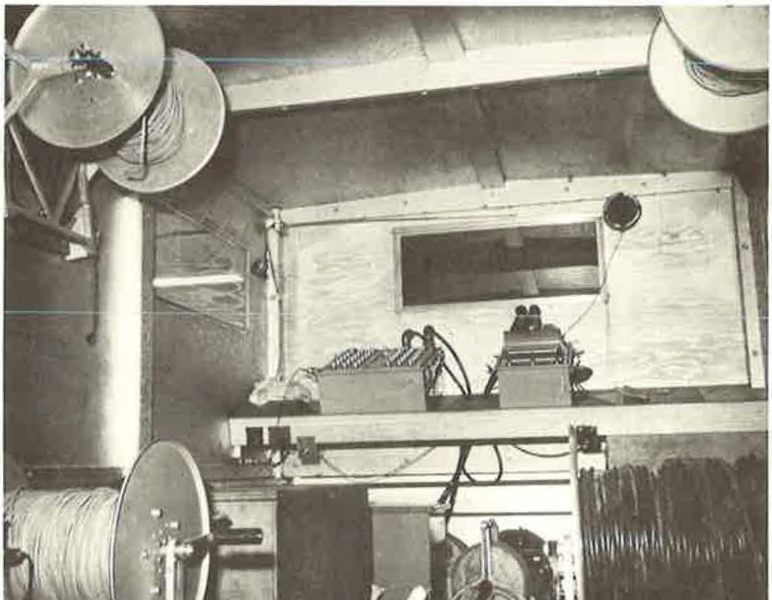


Figure 12. General view inside seismic truck showing Electro-Technical Labs 12-trace seismograph and reels of seismic wire.

Application and Interpretation of Seismic Method

Two methods of seismic surveying are presently being utilized by the Department. The first type is the more conventional seismic sounding where a geophone spread is laid out two to five times the desired investigation depth. A shot fired separately at each end of the geophone spread completes the sounding. Overlapping time-distance curves of this reverse sounding are then plotted, the interpretation is made, and layer velocities and depths to discontinuities are computed. The object of seismic profiling, the second method, is to obtain not the depths to particular discontinuities, but rather a relative subsurface profile of some good refracting horizon. By moving the geophone spread progressively out from the shot point, profiles over 3,000 ft in length can be obtained. Reverse profiles, always run, are a necessity for accurate interpretation.

The seismic profile data require very little mathematical treatment and can be immediately interpreted in the field. A time-distance graph of the profile data is drawn resembling any normal time-distance plot, except that the principal high-velocity part will be unusually long. This permits the interpreter to draw an extremely accurate, straight-line time-distance curve through the plotted geophone times. This straight line represents a flat horizontal plane of the high-velocity refracting material. The slope of this line is the reciprocal of the velocity of the material. The profile curve can then be interpreted. Variations in the surface of the high-velocity refracting layer from that of the level plane are apparent. In fact, the variations of the geophone time-distance plots from the straight-line plot represent the mirror image of the refracting horizon. The points below the line represent topographic high areas, whereas the points above the line represent topographic low areas. The relative amount above or below the line gives some clue as to the size of the high or low.

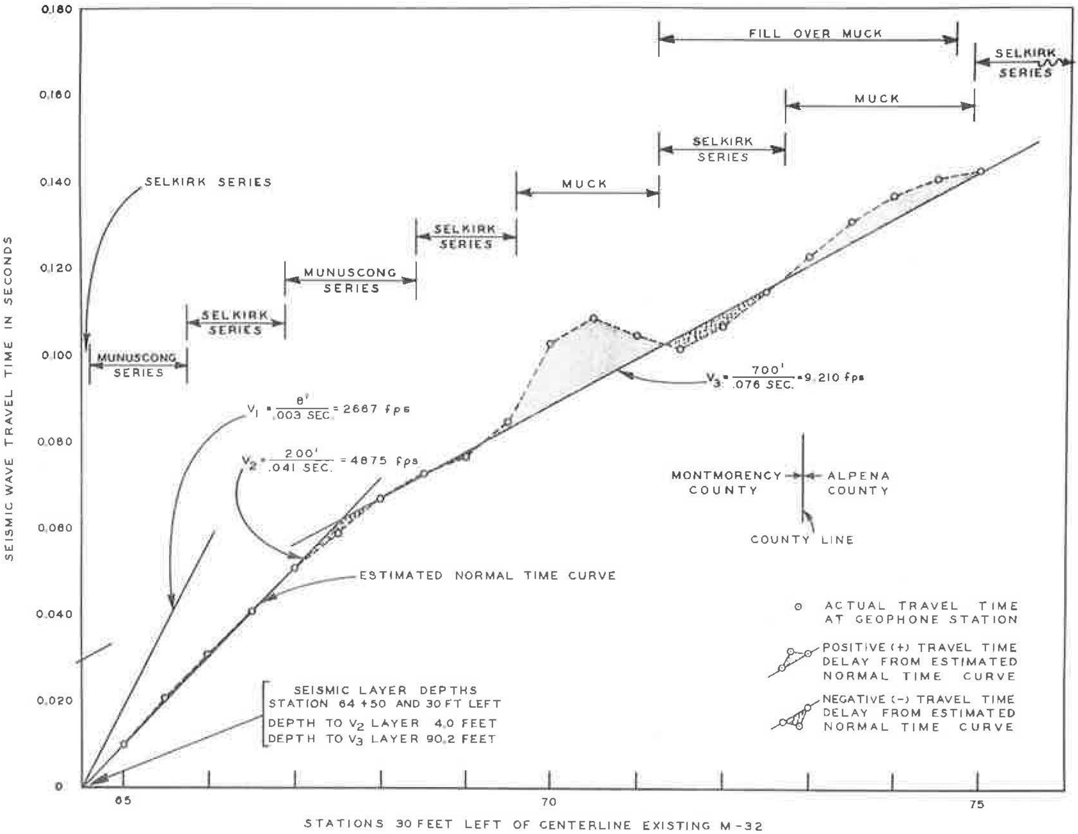


Figure 13. Refraction seismic profiles in relation to pedologic soils mapping.

When this refracting horizon represents the bottom of a muck swamp, the bottom of soft unstable sediments, or the top of bedrock, it is readily apparent that this information can be extremely useful, principally as a guide for setting up a boring or probing program for sounding out the area. The horizontal control or areal location of the high and low areas is excellent. The vertical control is only relative, and depth calculations can be considerably in error because they depend on velocity estimates of the overlying materials. The profiling method delineates the horizontal limits of the swamp. It also indicates the locations of deep and buried pockets. The results are not affected by thin high-speed sand or silt layers in the muck which could be probed as the bottom of the swamp. Parallel profiles across a swamp not only would pick out the buried pockets and deep areas, but also would give their size and lateral trends. The surveys are quickly made and the results are immediately available in the field without mathematical computations. It is believed that if the timing of the seismic profile survey can be made to correspond with the start of the drilling and probing operations, much of the uncertainty and guesswork can be taken out of swamp sounding. Figure 13 shows the correlation between refraction seismic profile data and pedological soils mapping.

USES OF GEOPHYSICAL SURVEYS

It has generally become departmental policy that all proposed roadway cut sections having cuts of 12 ft or more are surveyed. Resistivity soundings are normally made at each station and at least 3 to 5 ft below proposed grade. Depending on the situation, a single line of resistivity soundings may be run as on survey centerline. If the roadways are divided, several lines may be run which would include stations along each roadway plus lines left and right if side borrow is needed. Seismic soundings will also be made if it is believed that bedrock or Pre-Wisconsin till will be encountered.

A great deal of subsurface information is available in the cross-sections from profile contours. For the Road Design Division, an instant inventory is available of all the materials in proposed cut sections over 12 ft deep. The designer is made aware of the different soil types for the full depth of the cut section. He knows the relationship of the different soil and rock layers to proposed grade and drainage structures. He is also aware of the location of the water table and unusual soil conditions such as cobble zones. At present, many geophysical surveys are run as soon as preliminary grades have been laid, so that the survey information is available for use during laying of grades.

Geophysical survey reports are available to the contractors for bidding. Using these reports, the contractor knows the kinds and relative quantities of soil present for the full depth of the larger cut sections. This has taken much of the guesswork out of earth work, and in some cases has resulted in significantly lower contract bids. The contractor awarded the bid also receives copies of all geophysical surveys made in connection with that project.

Geophysical reports are also valuable during construction, in that an accurate inventory is available of the different kinds of soil in cut sections over 12 ft deep. Using these survey reports on larger projects, an earthwork schedule can be set up which will expedite construction. Clay cuts can be excavated in dry summer and fall weather, whereas the granular cuts can be saved for wet weather and winter grading. By this method, a project can be worked with very little time lost due to weather.

The Right-of-Way Division uses the survey reports for appraising and evaluating subsurface materials in buying right-of-way. If the parcel goes into litigation, the reports are used by the Office of the Attorney General as evidence regarding subsurface conditions and materials. Geophysical personnel may be called to testify as to the interpretation and text of the report.

BORROW PIT SURVEYS

Over half of all geophysical surveys are made on borrow pits. In some areas borrow presents little or no difficulty, but in others the location and acquisition of borrow becomes critical for successful completion of the job. A large borrow pit

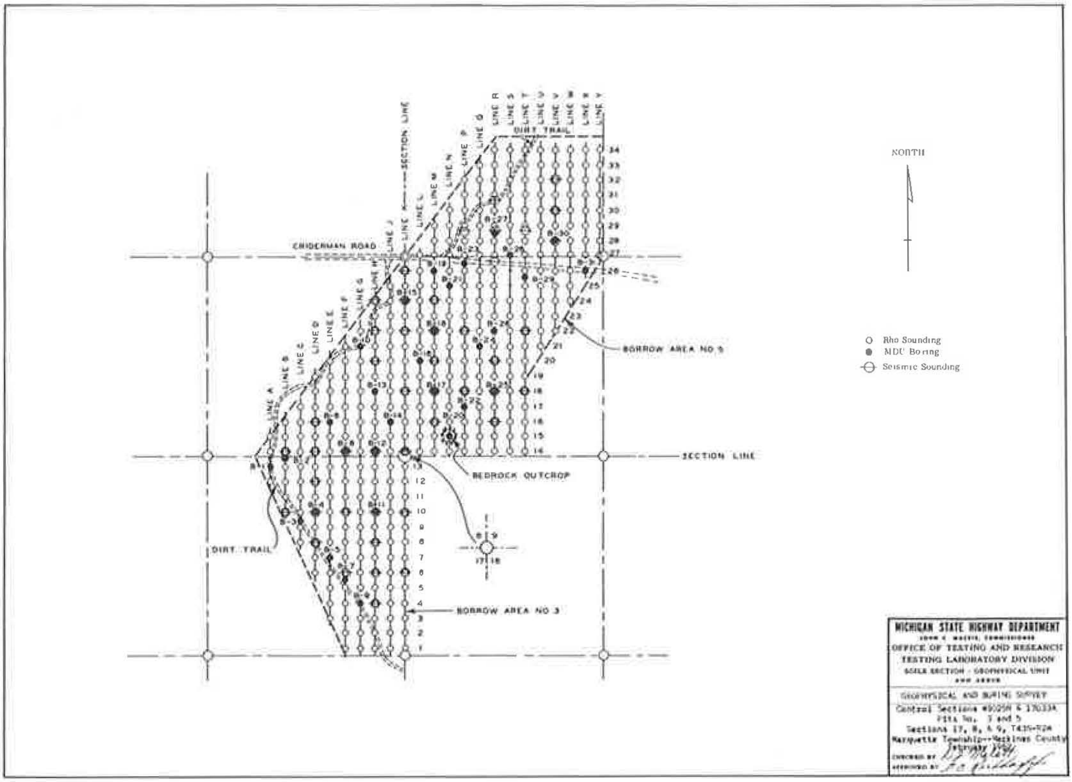


Figure 14. Borrow pit general location plan of resistivity and seismic survey.

yielding submarginal material can completely upset the planning, continuity, and economies of a project.

Michigan is divided into ten highway districts. Each district has a staff consisting of engineers representing road construction, bridge construction, maintenance, soils, etc. Each engineer is responsible to his particular division in Lansing. It is the responsibility of the District Soils Engineer to locate borrow sources. The quantities and kinds of borrow are determined by the Design Division. If the District Soils Engineer wishes a geophysical survey made on a proposed borrow area, he requests the survey by letter to the Soils Division in Lansing. The survey request is then forwarded along with a priority designation to the Testing Laboratory Division at Ann Arbor, where the Geophysical Unit is located. Priorities for geophysical surveys have been found necessary to co-ordinate the surveys into a statewide program. The survey request is then assigned to a Geologist Party Chief who conducts the survey. The type of geophysical equipment and survey method are generally determined at the unit level.

General techniques for surveying, interpreting, and reporting proposed borrow pits have evolved through the years. A series of parallel traverses are laid out across the proposed borrow area (Fig. 14). Stations are maintained at 100-ft intervals on traverses, and the distance between traverses is maintained at 100 ft. In essence, the area is covered by a 100-ft grid which can change depending on the glacial feature being surveyed. For example, an esker or crevasse filling will require one or more random traverses following the trend of the ridges. Engineering levels are made and a proposed base of excavation is determined by field observation in collaboration with district personnel and the property owner. The geophysical survey is then conducted using resistivity or seismic methods, or both, depending on the area and the information desired.

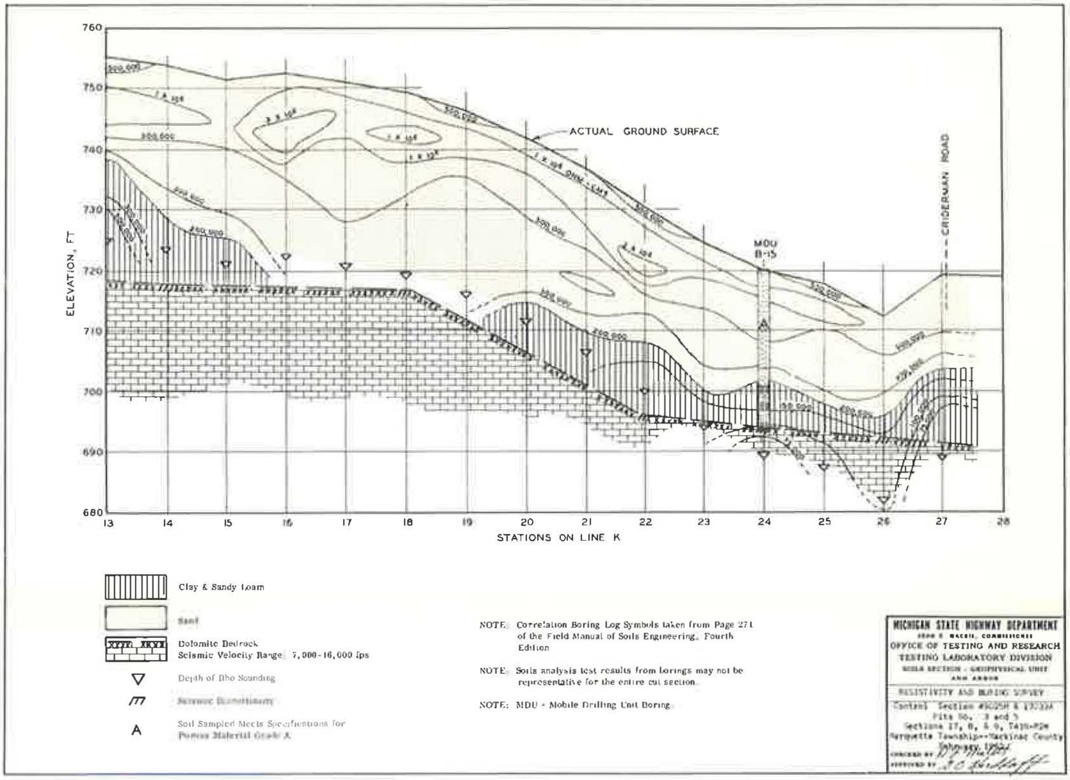


Figure 15. Cross-section from profile contours and seismic discontinuities.

No detailed geophysical survey is complete without correlation borings, because the same soil types will yield different geophysical range values, whereas different soil types will yield similar geophysical range values under varying environments. Correlation borings generally are made on a broad grid with five to eight station separations on traverses. Representative soil samples are taken and submitted to the laboratory for testing, to determine the physical properties of the different materials and their relationship to specification use.

The culmination of all survey data is the cross-section from seismic discontinuities and/or resistivity profile contours (Fig. 15). The cross-section shows the interpretations of the geophysical and boring information in the form of a geological cross-section. The boring logs and pertinent material specification information from the laboratory tests of boring samples are also included on the cross-section. The cross-section allows a quick evaluation of subsurface conditions and materials. With a series of such cross-sections from parallel traverses, estimated volumes of the various materials can be computed by the average-end-area method. Thus, even before a borrow area is purchased, detailed qualitative and quantitative subsurface information is available and can be evaluated in relation to other areas and to the job before commitments are made.

The completed survey report includes a written description of survey results, giving information relative to successful working of the area. Estimated volumes of the different materials and areal information are given. Laboratory test reports of the boring samples are also included. Finally, the cross-section sheets are included along with a general location plan of the area.

Copies of the survey reports are transmitted to interested divisions. The Design Division uses its copy in planning earthwork. The Construction Division uses its copies during excavation and as part of the U. S. Bureau of Public Roads file. The

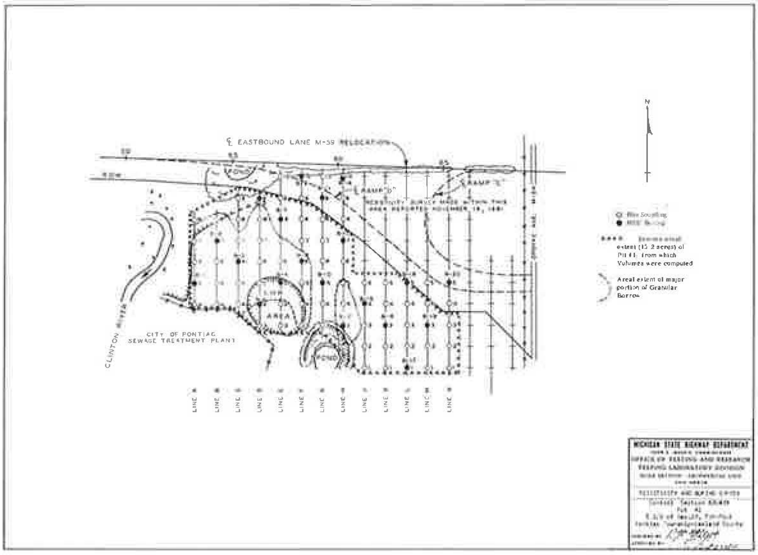


Figure 16. Borrow pit general location plan of resistivity survey.

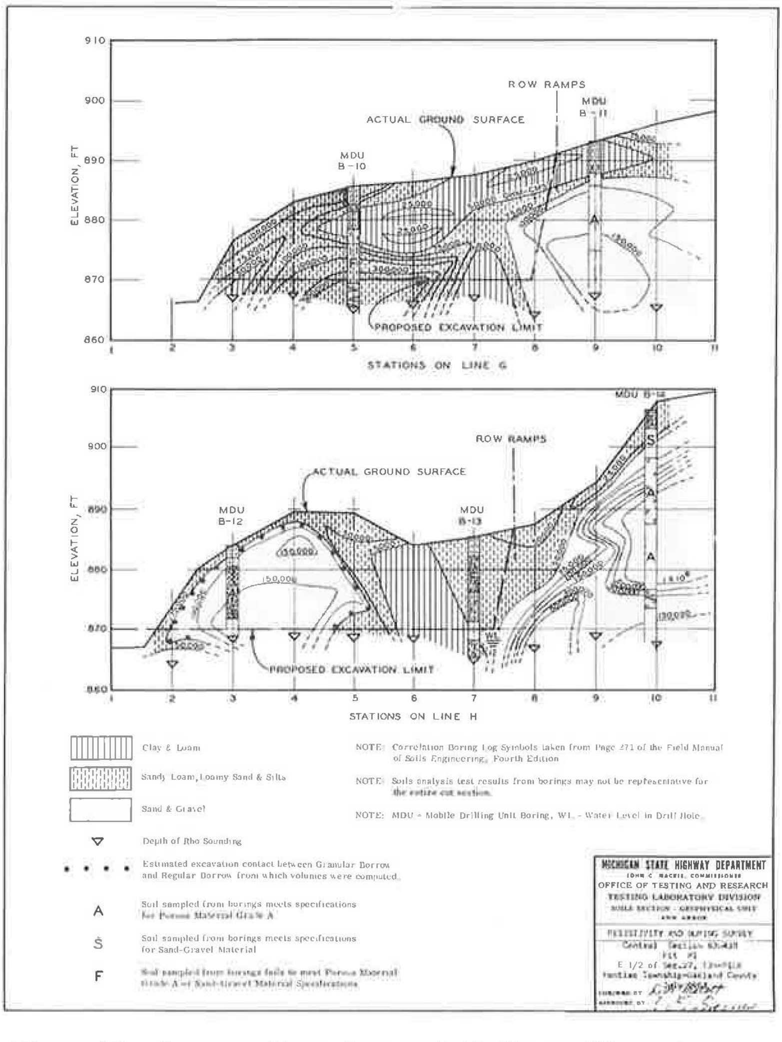


Figure 17. Cross-sections from resistivity profile contours.

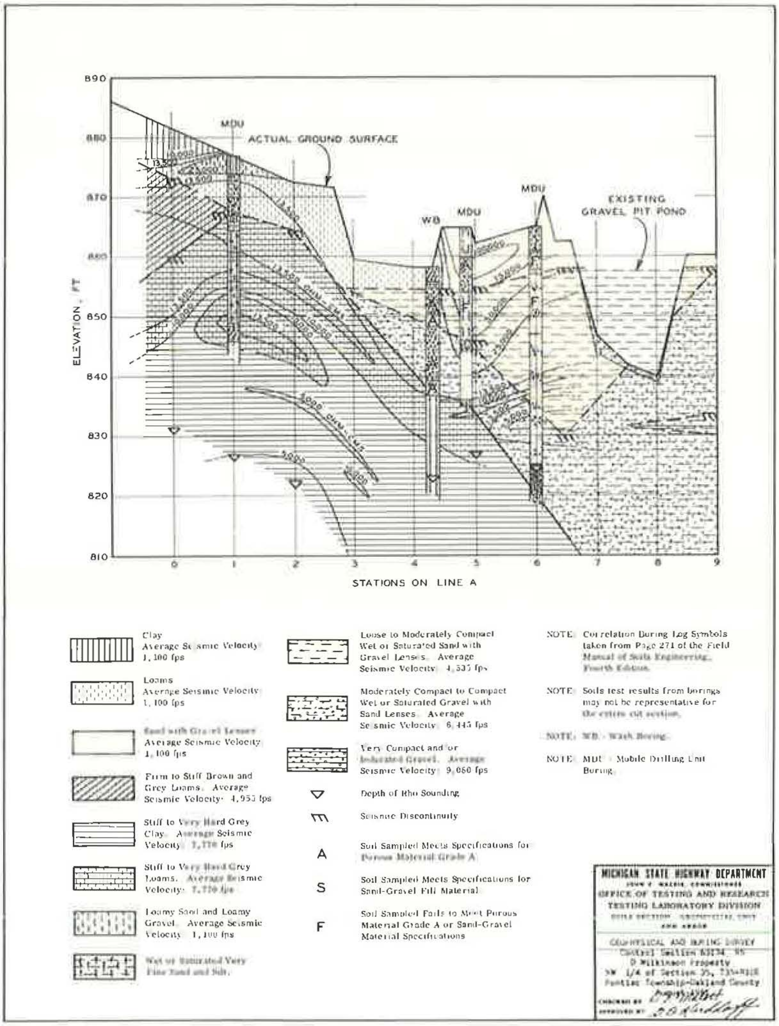


Figure 18. Cross-section from profile contours, seismic discontinuities, and borings of an underwater borrow pit.

Soils Division uses the information for borrow requirements. Copies are also made available to the Right-of-Way Division for property appraisal. The contractor receives a copy as a guide to working the area. The borrow survey reports are also discussed with the contractor at the preconstruction meeting in some district offices.

Borrow pits can generally be grouped into two major classes—dry or underwater—having their own peculiarities and requiring somewhat different treatments. The dry borrow pit may be located on a variety of glacial features, including eskers, kames, crevasse fillings, outwash, and various glacial-fluvial stratified till features. Most of these are ice-contact features and are characterized by rapid vertical and horizontal changes in texture. These deposits are generally surveyed by resistivity. Seismic soundings are included if bedrock might be encountered (Fig. 15). The subsoils are sampled with a truck-mounted continuous flight auger. Much care should be exercised in locating the borings so that representative samples are taken. Figure 16 shows a typical general location plan for a resistivity survey of a proposed borrow pit. The cross-sections from profile contours of resistivity traverse lines G and H appear in Figure 17.

Underwater borrow pits are generally located in river valleys, old glacial spillways, and glacial lake plains. They generally consist of various alluvial and lacustrine deposits such as valley trains, deltas, river bars, flood plains, off-shore bars, and other stratified till deposits associated with the ice front. Many of the textural changes in these deposits are gradational in character. Underwater pits are generally surveyed by both resistivity and seismic methods. Resistivity will obtain some contacts whereas the seismograph will obtain others. Between the two methods a good outline of subsurface conditions can usually be acquired. Figure 18 shows the cross-section of a typical underwater borrow pit examined by resistivity, seismic, and boring surveys. Correlation borings are made on a broad grid over the area. The continuous flight auger is not suited for procuring representative underwater samples, due to mixing. Wash borings with a split-spoon sampler are better, but the sample is small and sometimes difficult to obtain in gravelly materials. Wash samples give a good cross-section of the coarse materials but little information on the finer soil fractions. It has been found that combined resistivity, seismic, and wash boring surveys give the best information to date in underwater borrow areas. Recently, two large underwater pits excavated for the Interstate System turned out slightly better than indicated by the survey. These pits were worked in the wet with the material bailed out and allowed to drain 24 hr before use.

SPECIAL INVESTIGATIONS

Geophysical surveys are conducted for the Right-of-Way Division as an aid for making land appraisals when a mineral resource such as gravel or sand is involved. Similar surveys are also conducted for the Office of the Attorney General for mineral evaluation in litigations and damage hearings. The courts have accepted the survey

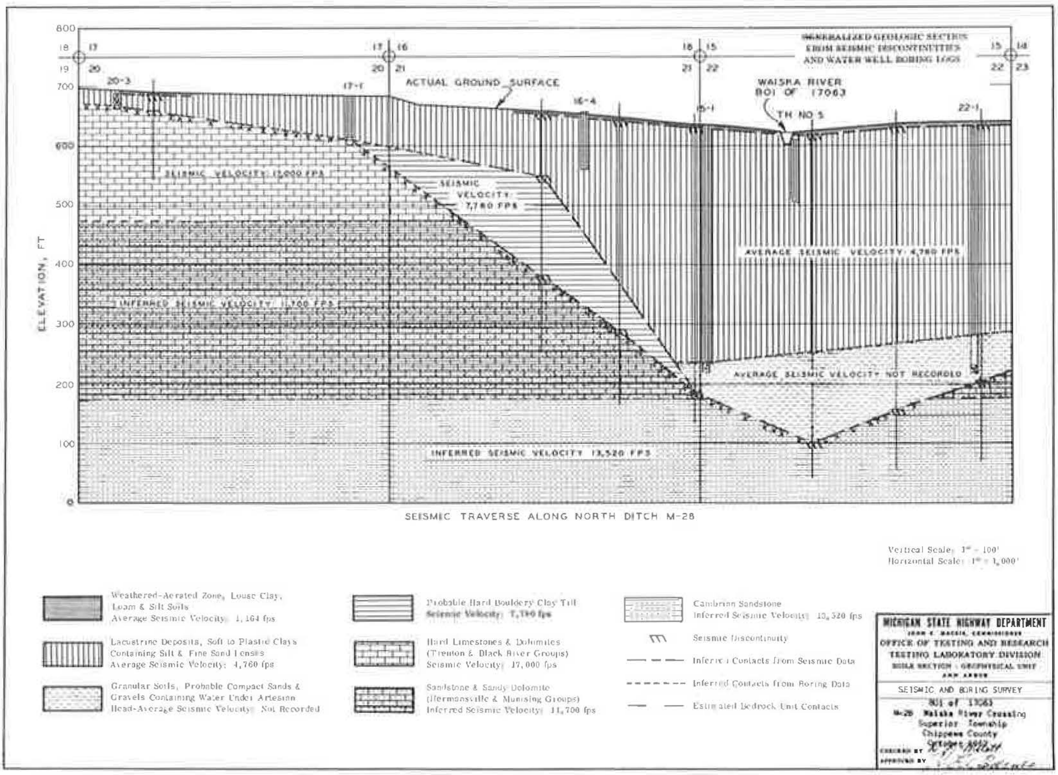


Figure 19. Geological cross-section of Waiska River Valley.

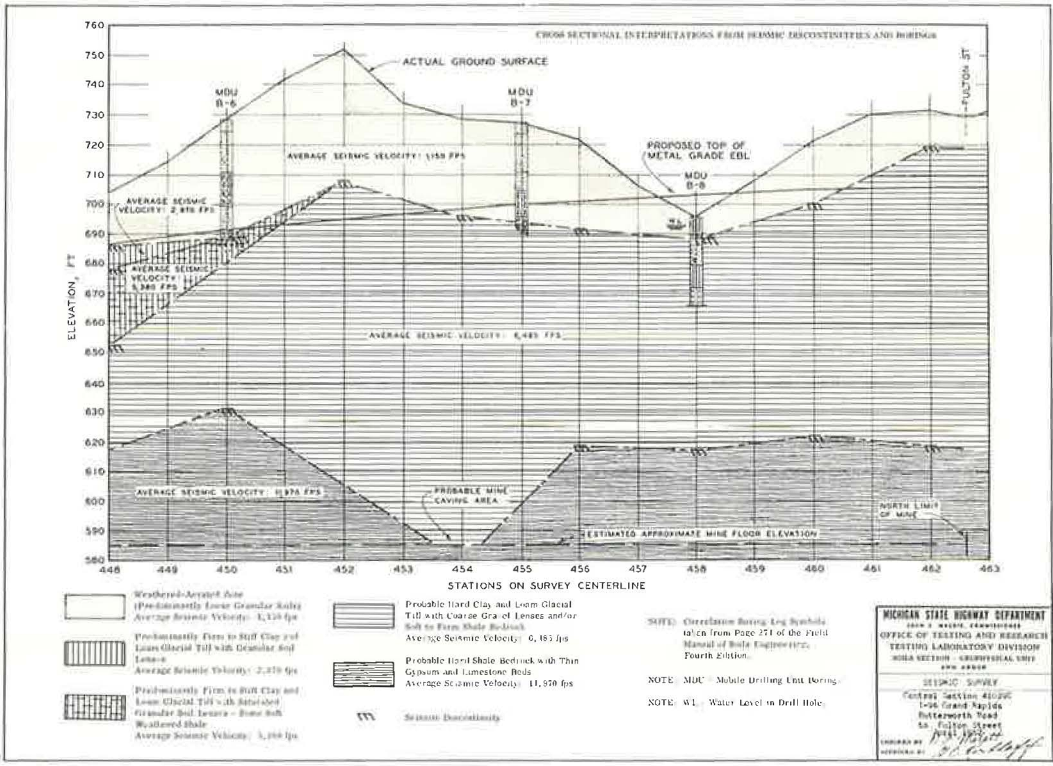


Figure 20. Seismic and boring cross-section showing bedrock and probable mine caving zone.

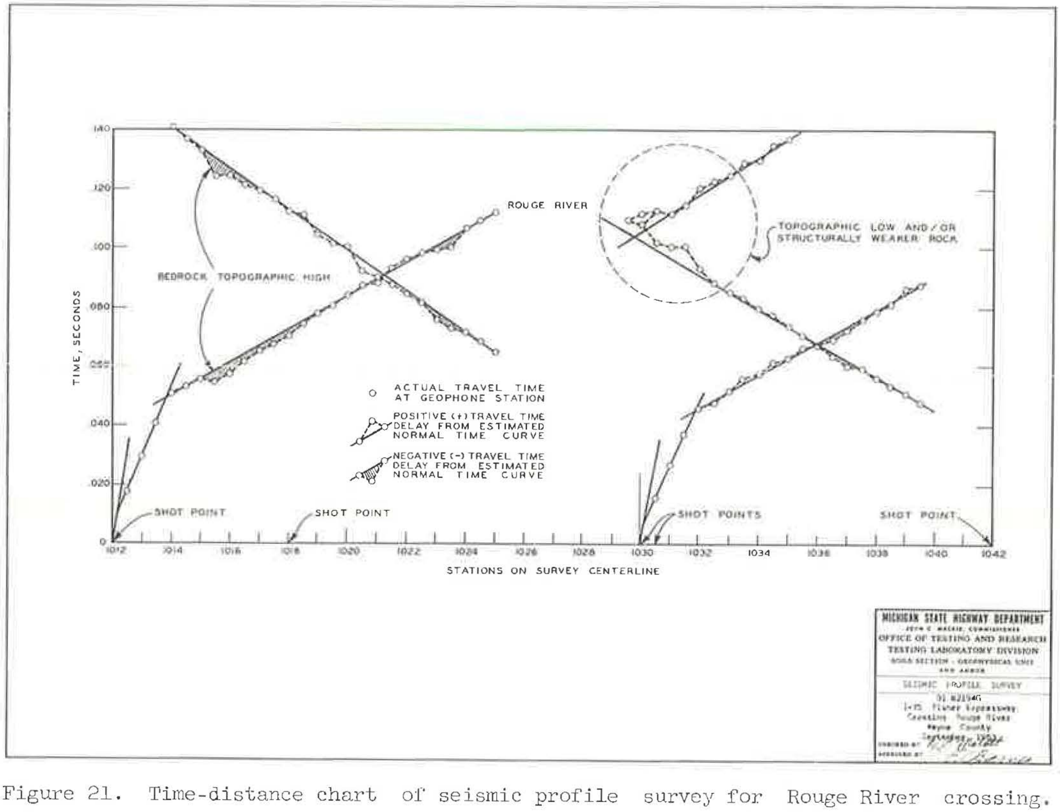


Figure 21. Time-distance chart of seismic profile survey for Rouge River crossing.

results, and many settlements have been made on the basis of the geophysical and boring results.

Geophysical surveys are requested when special subsurface problems arise. The Waiska River Valley was one such problem. Wash borings at the proposed bridge site for the M-28 crossing indicated an unusual depth of very soft lacustrine clay. A broad seismic traverse was run to obtain additional information (Fig. 19). Survey results indicated a broad preglacial valley filled with basal granular soil overlaid by a thick body of lacustrine clay. The cross-section showed that friction piles were indicated.

Part of the location of I-96 in Grand Rapids passed over an abandoned portion of a gypsum mine where some mine caving had occurred. A resistivity survey was conducted to outline the glacial drift and a seismic survey was made to outline the bedrock surface. The geologist in charge of the seismic survey entered the mine and inspected much of the area underlying the road location. The survey report gave a good picture of subsurface conditions and delineated one potential caving area (Station 454, Fig. 20).

An inspection of rock core borings at the I-75 High Level Bridge crossing the Rouge River in Detroit indicated a probable fault and weak rock zone. Seismic profile traverses outlined the problem area and led to additional rock core borings, which contributed to a decision to redesign the substructure. Figure 21 shows the time-distance chart of the seismic profile survey. The positive-travel time-delay zone between Stations 1029 and 1034 indicates a topographic low and/or structurally weak rock. This zone is to be grouted.

CONCLUSION

The various geophysical methods are not ends in themselves, but merely tools available to the engineer and geologist. Each method has its advantages and limitations which should be recognized and utilized. A great deal of useful and valuable subsurface information can be obtained by proper application of geophysical methods. Although the instrumentation and some of the mathematical treatment of geophysical data is a science, the interpretation of the data is still an art based largely on the experience and judgment of the interpreter.

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