HIGHWAY RESEARCH RECORD

Number 81

Geophysical Methods and Statistical Soil Surveys in Highway Engineering
6 Reports

Presented at the
43rd ANNUAL MEETING
January 13-17, 1964
and
44th ANNUAL MEETING
January 11-15, 1965

HIGHWAY RESEARCH BOARD
of the
Division of Engineering and Industrial Research
National Academy of Sciences—
National Research Council
Washington, D. C.
1965

Department of Soils, Geology and Foundations

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COMMITTEE ON SURVEYING, MAPPING AND CLASSIFICATION OF SOILS
(As of December 31, 1963)

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Foreword

A primary objective of the Committee on Exploration and Classification of Earth Materials (and its predecessor Committee on Surveying, Mapping and Classification of Soils) has been to acquaint highway engineering organizations with the current state of the art regarding subsurface exploration of soils and materials. Most of this information has been presented in symposia at Annual Meetings: soil mapping in 1961, materials inventories in 1963, and geophysical methods in 1964.

Contributors to the symposium on geophysical methods and applications reported that appropriate use of geophysical apparatus should result in more adequate subsurface investigations for highway projects, and hence result in better design, and may cause the overall subsurface investigation to be done at less cost than if dependence is based primarily on boring methods. Geophysical apparatus has been successfully used in: (a) estimating thickness of soil and rock layers or strata, and particularly determining depth to bedrock; (b) classifying soil and rock types; (c) determining the rippability of bedrock; (d) estimating extent of muck and swamp; (e) estimating extent (laterally and vertically) of sand-gravel deposits and select borrow; (f) estimating the position of the water table; (g) obtaining general information about the character of landslide materials and location of slip surface; (h) a preliminary stage or supplementing the boring program on highway projects; and (i) litigation, to supplement other subsurface information.

Natural environmental conditions such as frozen soil and complex or heterogeneous geologic materials, as well as man-made installations such as fences and utility lines, may affect geophysical measurements. Also, each type of apparatus has some inherent limitations. Consequently, some contributors recommended that extensive subsurface investigation programs be under the supervision of an experienced geophysicist, and that the geophysicist have a working knowledge of geology or that a geologist assist in the work. The project report by the geophysicist should indicate any inadequacies of the method and what supplemental information should be obtained by other subsurface exploration methods.

This publication also contains the following additional information:

1. "Status of Published Soil Surveys, October 1, 1964" which supplements the 1957 list in Highway Research Board Bulletin 22-R. Since many of the recent county or area soil survey reports contain an engineering applications section, the committee decided that Bulletin 22-R should be updated. Supplemental lists of soil survey reports will be given at intervals of a few months in appropriate Highway Research Board publications. Although the lists of the libraries and Soil Conservation Service personnel in Bulletin 22-R also need to be updated, it was decided that, because of the work and cost involved in republication of the complete bulletin, the updating of those lists would not be undertaken for several years.

2. An abridgment of a paper by T. K. Liu and T. H. Thornburn entitled "Statistically Controlled Engineering Soil Survey." The complete manuscript is published as University of Illinois, Civil Engineering Studies, Soil Mechanics Series No. 9. Copies of that publication can be obtained from the authors.

Contents

Introduction

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•THOROUGH SUBSURFACE exploration to determine the location and conformity of bedrock and the extent and general characteristics of layered surficial materials, which are needed for highway location and design, may require considerable drilling. Indirect means of obtaining subsurface information should be used when feasible to supplement or displace drilling or augering methods.

Papers in the 1961 symposium on soil mapping (1) and the 1963 symposium on materials inventories (2), as well as correspondence between the Committee on Surveying, Mapping and Classification of Soils and state highway departments in arranging those symposia, indicated that a variety of geophysical apparatus was being used in highway subsurface investigations. Also, a 1960 questionnaire on subsurface exploration (3) showed that 26 of the 50 state highway departments were using geophysical apparatus for determining the depth to bedrock, locating sand-gravel deposits, and other purposes. During the last few years, several types of lightweight geophysical apparatus have been developed. Consequently, the Committee decided to arrange this symposium to present the state of the knowledge on geophysical methods and applications.

In developing the symposium program, the Committee asked each state highway department wishing to participate in the program to submit a brief outline of the proposed paper. Some states replied that they were interested in obtaining information on geophysical methods, but had not used such apparatus or had used it to only a limited extent. Some states had one type of apparatus, but wanted information about other types. Members of the Subcommittee on Soil Surveying and Mapping reviewed the submitted outlines and selected five papers that : (a) are representative of seismic and electrical resistivity methods, with some recent types of apparatus being represented; (b) describe the various highway applications of the apparatus; (c) represent work in various geographic and general geologic areas; and (d) give some cost information for this type of investigation.

In reviewing the submitted outlines, it was found that some new types of apparatus have not been fully evaluated. It is hoped that these evaluations will soon be completed and that results will be published to supplement the information presented here. The highway departments will then be in a better position to decide the best geophysical equipment outlay to fit the conditions of the specific state.

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Seismic Surveying Methods, Equipment And Costs In New York State

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Seismic surveys for highway location, design, estimate and construction purposes have been conducted since 1948. Since 1956, two complete parties have been continuously engaged in these operations throughout each year, winter and summer.

This paper describes the methods and equipment used in performing seismic surveys for highway engineering purposes. Also included are the total and unit costs involved in maintaining the parties and equipment and conducting the surveys.

•THE Bureau of Soil Mechanics of the New York State Department of Public Works has been utilizing geophysical methods of exploration in its highway, bridge, and building design and construction programs since 1948. In the beginning both the seismic refraction and electrical resistivity methods were tried. However, it was soon found that, with few exceptions, the seismic refraction method gave better answers to the engineering problems involved. At present, electrical resistivity surveys are used by the Bureau primarily as an aid in locating buried aquifers for subsurface water supplies at various state institutions and facilities.

More recently the shallow reflection method, using high-resolution seismic systems has been tried by the Bureau on some special problems. Further equipment development will undoubtedly increase the usefulness of this method; however, the refraction method is still the best approach to the average engineering problems that are encountered in New York State. This is due in part to the complex geology in the areas where most of the seismic work is carried out.

Seismic survey data are utilized by the Department primarily for design and estimate purposes. All subsurface information, including seismic data, is made available for the inspection of the bidders prior to letting. Such data are considered extremely important in preparing bids because New York State excavation specifications are on an unclassified basis.

The first seismic investigations made by the Bureau were conducted by Paul H. Bird, at that time the only engineering geologist employed by the Department. He quickly proved the worth of the method to the Department. Gradually, additional personnel, mainly geology graduates, were hired under technician titles to assist with the field operations. Because there were no permanent positions in the Department for additional geologists and, therefore, practically no chance for advancement, the personnel turnover was very high. Despite this, the Bureau maintained two crews in the field during much of the time between 1950 and 1956. Six permanent engineering geology positions were added to the Bureau's roster in late 1956. This immediately minimized the geologic personnel retention problems. Two seismic parties, composed of engineering geologists and laborers have been in the field constantly since that time.

At present, the engineering geology staff of the Bureau consists of one associate, one senior, four assistant and six junior engineering geologists. As many as eight of these men may be engaged in the seismic program at one time.

Paper sponsored by Committee on Surveying, Mapping and Classification of Soils and presented at the 43rd Annual Meeting.

METHOD

The theory of the seismic refraction method is simple and straightforward. It follows the laws and principles of optical geometry; that is:

1. Snell's Law: The sine of the angle of incidence is to the sine of the angle of refraction as the velocity in the first media is to the velocity in the second media.
2. Fermat's Principle: The shortest time path between two points is in accordance with Snell's Law.
3. Huygen's Principle: Each point on a wave front may be considered as a source of new wavelets which travel outward in the direction of propagation.

The interrelation of these statements is best illustrated in wave front diagrams. The construction of wave front diagrams for a series of special problems is one of the first steps used by the Bureau in familiarizing new employees with the seismic method.

The application of the refraction method consists of recording the time that it takes the seismic pulse from an energy source to arrive at successive stations, generally in a straight line with the origin point. A time-distance plot of these arrival times is then made, which gives velocities and angular relationships which are used in calculating depth. Certain inferences regarding the material underlying the seismic line may be drawn from the velocities.

For the method to work, certain physical requirements should exist in the area being investigated: (a) successively deeper layers should have successively higher velocities; (b) each layer must have a certain minimum velocity to thickness ratio in relation to the velocity to thickness ratio of the overlying layer and the velocity of the underlying layer in order to show up on the plot of first arrivals; and (c) velocities should remain constant laterally over the length of the seismic spread. Practical considerations make it evident that these conditions are often violated, especially in Pleistocene ice contact deposits. However, the wavelengths of frequencies that can propagate in natural earth materials are long enough so that minor deviations from the theoretical can be tolerated. Larger deviations from the theoretical case often show on the seismogram, giving valuable, if negative, information. For instance, in the first problem, a velocity inversion will often show up as a "skip" in the time-distance curve. This is a clear indication that a low velocity layer exists beneath a relatively thin high velocity layer. In granular materials, an inversion could mean a clay layer with the possibility of a perched water table. Considerable additional information can be gained in these cases by using record characteristics as well as the arrival times. The second and third problems are more instrumental than anything else, since their final solution depends on secondary breaks.

A basic rule followed by the Bureau of Soil Mechanics in applying the seismic method is to control everything possible at the field level. Precise systematic field work will eliminate many problems in interpretation. This means that all profiles, or seismic lines, must be reversed; i. e., shot at each end. Further, all reported shot points should be tied; i. e., common to two or more profiles.

One factor that can be controlled in the field is the effect of topographic irregularities. Any change in the general ground slope along the seismic line may result in ambiguous data. This does not mean that the data are useless, but it does mean that the topography must be accounted for in the interpretation of the data. Because topographic corrections in complex soil profiles are often difficult to make, it is better to lay out seismic lines so that changes in general ground slope are avoided wherever possible.

Another problem that can sometimes be controlled in the field is the velocity inversion caused by a thin layer of frozen ground. The wavelength of the lowest frequency that will propagate in a media is approximately equal to four times the thickness of that media. Briefly, the "skip" in the time-distance plot of Figure 1 is due to the fact that the relatively high frequency energy traveling in the high speed frozen ground dies out before the normal arrivals from the V_2 layer are due to arrive. At some previous point, the energy had diminished to the point where it could no longer sustain refractions down into the V_1 layer. It should be noted that as the frozen layer becomes

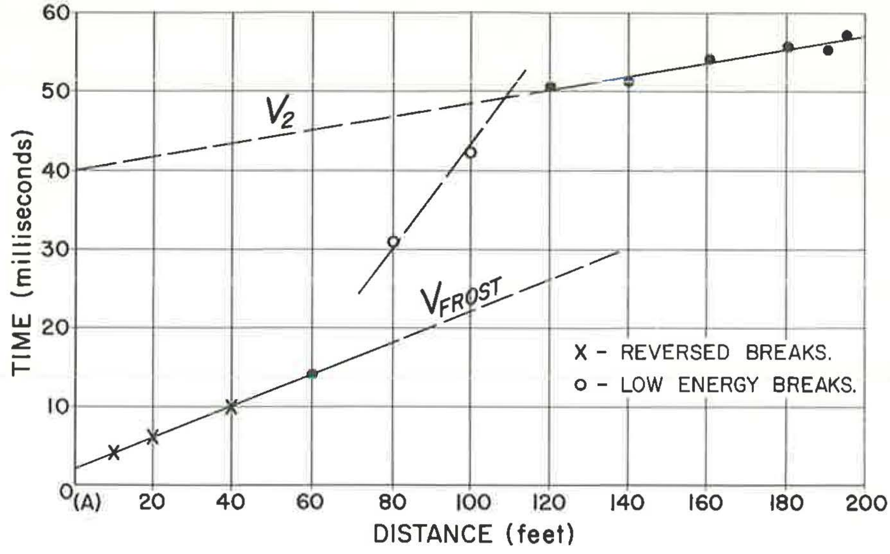

Figure 1. "Frost breaker" plot.

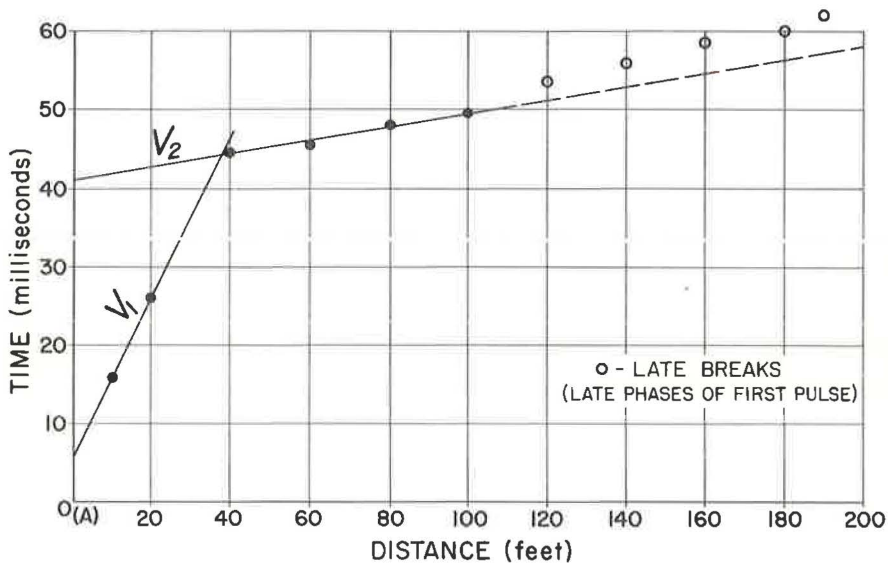

Figure 2. Small shot—following "frost breaker."

thicker, the energy lasts longer and the "skip" diminishes and finally disappears leaving a normal looking record except for some reversed breaks. Reversed breaks near the origin are common in frozen ground due to the angle at which the wave front strikes the seismometers. Although this problem can be solved theoretically if all the velocities involved are known, this is seldom the case. Therefore, it is better to eliminate the problem wherever possible. One way to do this is to use two shots at every shot point. The first shot is a relatively large shallow one, generally 1 to 2 lb, placed just below the frozen layer in two or three closely spaced holes. This shot is used to break up

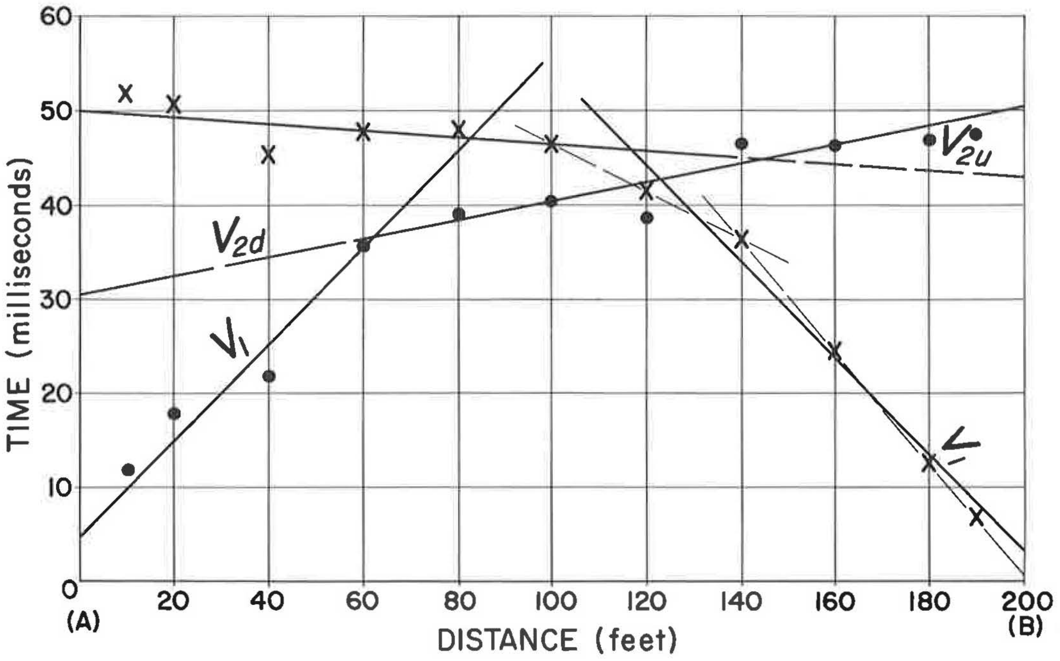

Figure 3. "Balance point" method.

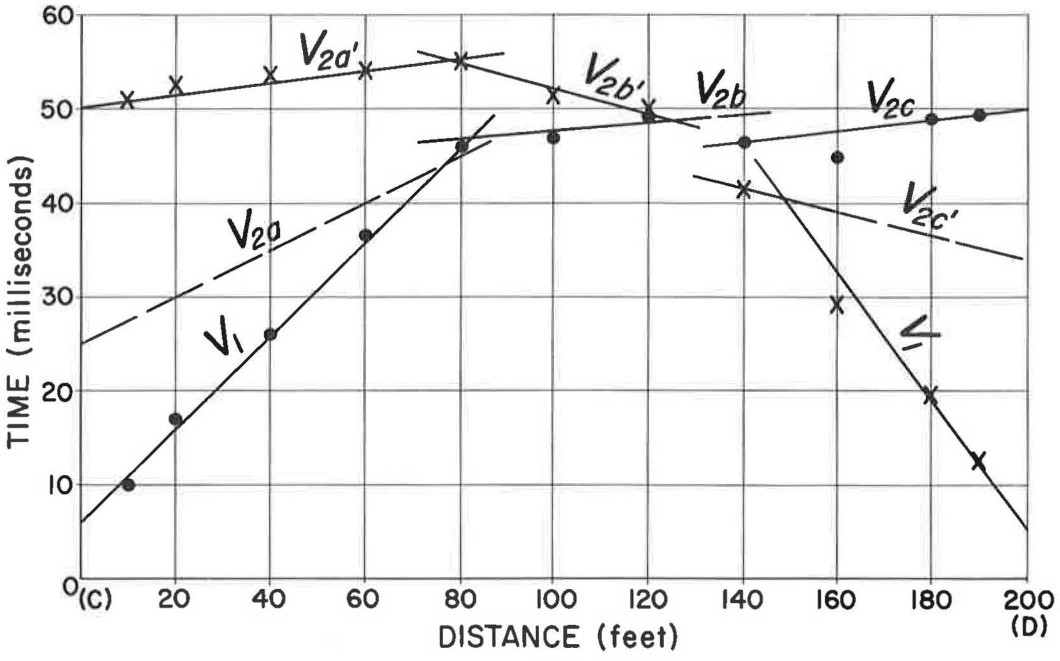

Figure 4. "Matched velocity" segments.

the frozen ground. The second charge is a very small one placed in the hole blown out by the first. The record from the first charge gives a valid rock line on the time-distance plot (Fig. 1), because, as long as the velocity of the rock, or whatever the second layer happens to be, is higher than the frozen ground velocity, the arrival times of the refracted wave will be affected by the frozen layer only on emerging. For thin frozen layers the effect on accuracy is negligible. The record from the second charge will usually give the surface velocity plus one or two arrivals on the rock line before the energy drops off (Fig. 2). Records from both charges may be combined to give a valid time-distance plot. Although this method is not feasible in some areas due to local culture or excessive thickness of frozen ground, it does permit seismic operations to continue in much of New York State during the winter months.

The reading of the seismic records is simply a matter of making the proper "picks" inasmuch as the cameras presently in use by the Bureau are equipped for two millisecond time lines. Good seismic breaks can be read to the nearest 0.5 millisecond. The actual drawing of the velocity line is done either by a balance point method or by a velocity segment method. Under the balance point method, readings that are late or early in one direction of a reversed profile are made late or early in the other direction (Fig. 3). If the relationship between the corresponding points on the reversed profile were not considered, the "B" end of Figure 3 could be misinterpreted as a three-layer problem, as shown by the dashed line. This system implies that the majority of the deviations are due to local near-surface differences. When this procedure will not fit the observed data, it usually means that the seismic interface will not fit an average line between the two shot points. Therefore, matching pairs of velocity segments are used. An example of this is shown in Figure 4, where the true velocity of V_2 may be determined from segments V_2b and V_2b^1 and the velocity of the segment V_2a found from the true velocity and the segment V_2a^1. Because V_2c is parallel to V_2b, V_2c' is drawn parallel to V_2b^1. One or the other of these methods combined with the information from the adjacent lines will usually give an unique solution. Statistical methods are used only when the record quality is very poor.

All computations done by the Bureau's seismic parties are based on theoretically correct formulas, most of which are dependent on "critical distance" (the distance from the origin at which the velocity lines intersect). These formulas are more accurate in practice than the time-intercept formulas (based on the time at which the extension of the velocity lines intersect the time axis). One reason for this is that small errors in reading the time intercept from the time-distance plot have a much greater effect on the calculated depth than do corresponding errors in reading the critical distance at the scales most commonly used in plotting shallow refraction data. For example, when $V_1 : V_2 = 1 : 2$, the effect on calculated depth of an error of one millisecond in reading the time intercept is equal to the effect of an error of almost 10 feet in reading the critical distance.

Constant charts and a mechanical calculator, which gives true velocity, mirage distance, constants, and dip angles, are used in the computations. Velocities are read directly from the time-distance plot simply by taking the number of feet traveled in 10 milliseconds and multiplying by 100 to obtain feet per second.

The actual plotting and calculating procedures are carried out in the field so that the best interpretation of the data can be made in the light of the local topographic and geologic conditions. The work sheets and report forms are reviewed in the main office of the Bureau before the final report is issued. Outcrop maps and geologic reports are submitted along with the seismic report wherever necessary.

EQUIPMENT

In general, it is the purpose of a seismic system to record the time that it takes a seismic pulse to travel from its origin to various recording stations along a governed path. In the shallow refraction method, we are primarily interested in the first pulse to reach any given station—i. e., the one that followed the shortest time path. There are certain criteria which are absolutely necessary to any seismic system:

1. It must have an accurate and easily read timing system.
2. It must have sufficient amplification so that the first pulse is recorded throughout the entire length of the seismic line (generally at least four times the depth of interest for control).
3. It should reproduce the incoming signals with a minimum of distortion and delay.
4. It should be rugged enough to withstand hard usage.

The original equipment purchased by the Bureau was a three-trace seismic system, consisting of carbon granular seismometers, string galvanometers and a 35-mm movie camera. The system was insensitive and required a rather large explosive charge to investigate to nominal depths. It was slow because it had only three recording channels. The film records were also inconvenient to process.

Two Century 12-trace portable refraction sets were purchased in 1950. These sets used electromagnetic pickups, push-pull amplifiers, D'Arsonval type galvanometers and recorded on photographic paper. The timing system was a vibrator-controlled motor-driven disk which gave 10-millisecond time lines. These sets were used by the Bureau until 1958, when they were replaced by two Texas Instrument 12-trace high-resolution systems.

The high-resolution systems are very versatile because of their wide frequency response, filter selection and high gain. Recording is similar to Century. Each unit is equipped with a tuning fork-controlled motor-driven drum which places time lines across the paper every two milliseconds. These units are used with a variety of land and underwater seismometers.

A small self-contained 12-trace Electro-Tech Instrument which records on Polaroid film has recently been purchased for use where access is extremely difficult. This set, in combination with a Century camera modified to give two-millisecond time lines, will be used to instrument a third seismic party.

Transportation is a problem in many areas in which seismic survey work is done. For this reason, each seismic system of the Bureau is mounted in a special body built on a four-wheel drive Dodge "Power Wagon" WM 300 pickup truck equipped with a front end winch. The truck body is constructed so that it is always ready for operation. The instruments are mounted in a separate light, tight compartment which is entered by a door located on the side of the truck (Fig. 5). Photographic supplies, spare parts, drafting equipment, etc., are stored in built-in cabinets in this compartment. The cables, shot lines, digging tools, etc., are stored in shelves which are entered from the rear of the truck. The use of seismic cable extensions up to 1,000 feet in length makes it unnecessary to remove the equipment from the trucks, except in rare instances.

Figure 5. Seismic truck—door to instrument compartment is just forward of right rear fender.

TABLE 1

SUMMARY OF COST ANALYSIS (1962)

Factor	Value
Total cost, 1962[a] ($)	100,895
Production:	
No. of determinations[b]	2,489
No. of ELF (equivalent linear feet, depth)[c]	138,570
No. of determinations/day/party	5
No. of ELF/day/party	278
No. of stations/day/party	10
Unit cost ($)	
Per determination	40.50
Per ELF	0.728
To maintain each party/working day	202.000

[a]Including salaries, "fringe benefits," travel expenses, automotive expenses, supplies, parts repairs, and depreciation of seismic and vehicular equipment.
[b]A determination consists of an average of 2 "shots."
[c]The "equivalent linear feet, depth" for any determination is based on the number of feet that would have to be drilled to determine the depth to the surface of bedrock (usually depth to rock plus 10 feet into rock to differentiate from a boulder, or cut depth plus ten feet—whichever is less).

During the winter months, much of the work is done on snowshoes. Whenever it is necessary to remove the equipment from the trucks, it is mounted in special racks built on fiberglass "snow boats." These snow boats are pulled by a motorized toboggan.

Each party is also equipped with a six-passenger station wagon for transportation of personnel and supplies to and from the project. The seismic trucks are left in the project area until the seismic work is completed.

COST OF SEISMIC SURVEY OPERATIONS

The Bureau maintains accurate cost accounting records of its seismic survey operations. A summary of the cost analysis for 1962 is given in Table 1. Because the outcrop maps and geologic reports are considered as essential parts of the seismic program, no attempt has been made to separate the costs of the two phases.

CONCLUSIONS

Based on 15 years' experience with the seismic method of subsurface exploration for public works engineering purposes, it is the opinion of the Bureau of Soil Mechanics that the seismic method presents a rapid, economical, and satisfactory exploration tool, provided the following conditions are met:

1. Properly trained personnel of adequate experience are employed. It is the opinion of the Bureau that seismic survey and interpretation personnel have an engineering geology education and experience background.
2. The seismic instrumentation system is capable of faithfully and consistently recording arriving pulses. In general, simplified insensitive equipment will not consistently provide usable data within the range of depths that is of interest to the highway and building designer.
3. The method is used on problems to which it is suited. Each method of subsurface exploration has its limitations. The seismic method is no exception in this respect. It is, therefore, necessary for any user of seismic survey information to realize the limitations of the method and not attempt to apply the method to problems to which it is not adaptable.

Seismograph Operations by Maine State Highway Commission

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Refraction seismograph exploration methods are described as applied to highway soil surveys in Maine. The growth and expansion of the soils program necessitated the development of a rapid method for the identification and delineation of soil and bedrock. The selection of the seismic rather than the electrical method appeared to be the logical choice in view of the speed with which results can be obtained and data reliability.

The problems of equipment selection are discussed. Most important of these was the decision in favor of a 12-channel system over the recently available single-channel counter system. The equipment installation is described with emphasis on its rugged construction and its ability to give long, trouble-free service. The personnel requirements are specified and the duties of each of the five men on the field crew are described.

The paper also describes the operating procedure of the seismograph. The greatest operational problem is the interpretation of data, and specific examples of time-distance plots and their solutions are presented. A comparison is made of the original data with borings, test pits and road cuts to develop confidence in the seismic method.

•IN November 1961 the Maine State Highway Commisssion purchased a refraction seismograph system for the soils division. The purchase stemmed from the increased demands for soils information by the construction divisions and the need for a rapid method of determining the depth to bedrock. The older method of probing with iron rods and hammer was too slow and led to erroneous evaluations because the rods could be stopped by boulders or rocks. Other uses for the system could be (a) identification of soil types and detection of the contacts between different soils, (b) the study of highway materials deposits, and (c) the detection of the water table. In addition, since the equipment was purchased, it has been used in the study of bridge sites and in the study of soft materials in fill sections.

SEISMOGRAPH TECHNIQUE

The seismograph technique is based on the measurement of the velocity of shock waves generated by the detonation of a charge of dynamite. The velocities of the waves are obtained through the interpretation of data recorded by the seismograph instruments, and are used in calculating the depths of the various layers of soil and bedrock.

The seismograph technique is usable only where a contrast exists between the velocities of the various soil materials. For example, in an area composed of silt over sand over bedrock, the seismograph could not distinguish between the two soil types if their shock wave velocities were the same.

The seismic velocities, along with geologic data, are an aid in the identification of soil types. Table 1 gives the velocity ranges for soils and bedrock that are found in Maine. The ranges of several soils overlap and the range of dense till or hardpan

Paper sponsored by Committee on Surveying, Mapping and Classification of Soils and presented at the 43rd Annual Meeting.

TABLE 1

RANGES OF VELOCITIES OF SOILS AND BEDROCK FOUND IN MAINE

Soil or Bedrock	Velocity Range (ft/sec)
Sand	1,000-2,500
Gravel	2,500-4,000
Clay and silt	2,000-8,000
Loose till	1,500-4,000
Dense till (hardpan)	4,000-10,000
Bedrock	9,000-20,000

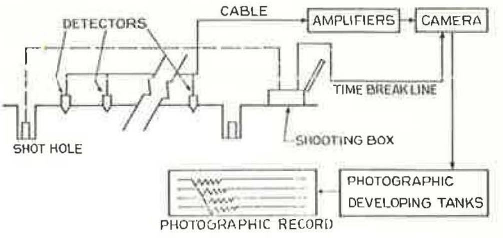

Figure 1. Complete seismograph system.

overlaps that of bedrock. Therefore, further evaluation by means of wash borings or test pits is required for positive identification.

A complete seismograph system is shown in Figure 1. The detectors, or geophones, are placed in the ground, generally no deeper than a few inches, in a line 200 feet in length and connected to the instruments through a multi-conductor cable. This layout is called a "spread." At each end of the spread, a hole called a "shot hole," 2 or 3 feet in depth is made in the ground to accommodate a small charge of dynamite. The detonation is triggered by a special battery-powered shooting box, and the exploding dynamite generates shock waves which radiate into the soils and bedrock.

Some of the shock wave energy returns to the surface and actuates the detectors. This energy is converted into weak electrical impulses which are amplified and used to operate the mechanisms of the recording equipment, called a "camera." The camera produces a photographic image of the shock energy on light-sensitive paper which is then processed and used by the interpreter for obtaining the shock wave velocities.

SELECTION OF EQUIPMENT

A multi-channel system was selected as being most suitable for large-scale seismic surveys. Other advantages are (a) the energy source is common to eleven or twelve points, (b) the data are recorded on adjacent camera traces, and (c) a permanent record is made of each shot. Problems associated with the energy source can be identified and eliminated or their effects taken into account in the interpretation. Minor variations in energy amplitude and pulse shape can be used to identify the exact arrival time of the refraction energy. Also, extraneous noise, which in most cases occurs on several traces, can be easily identified from the refraction energy.

The identification of refraction arrivals is a major part of the interpretive process, and the ability of the interpreter contributes to the usefulness of the multi-channel system. The interpreter may apply new ideas to his methods and thereby improve the quality of the information. This is most easily accomplished with data from a multi-channel system.

In the single-channel seismograph system the positions of the detector and energy source are interchanged. Only one detector is used, and the energy source is a hammer struck on a steel plate. The detector is placed at the position equivalent to the shot hole in a multi-channel spread, and the hammer and plate are located successively at each multi-channel detector position. Therefore, because the source is moved after each observation, the character of the energy is not necessarily uniform.

The arrival time of the energy is measured by an electronic timer and is read on numbered lights on the instrument panel. The energy pulses must be of the proper shape and amplitude and must be free of extraneous noise to control the timing circuits properly. The single-channel unit does not provide a permanent record for later re-interpretation, although several manufacturers may now market recording devices. One such unit contains a cathode-ray tube display, but the display is of a temporary nature. Another problem may be the noise created by the hammer blow on the plate, such as was found in tests with this energy source and the multi-channel system.

INSTALLATION

The system is installed in a four-wheel drive carry-all truck with a front-end winch and a 100-ampere battery charging system. The two rear seats were removed and the instruments mounted on a special inclined table behind the driver's seat. Beside the instruments is a plywood light-tight cabinet equipped with armholes and photographic-chemical tanks. This is the "darkroom" where the light-sensitive paper bearing the seismic data is processed.

A small table is installed in the rear of the truck for the interpreter where he can work independently of the instrument operator. The cables and other unmounted equipment are stored beside the interpreter's table and are easily removed through the rear doors of the truck.

The design of the installation was guided by the need to shoot remote areas on the proposed Interstate Highway System. The relatively small, compact four-wheel drive truck contributes greatly toward meeting this requirement but some areas cannot be reached by vehicle. Therefore, jumper cables, available in a total length of 3,250 feet, are used between the truck and the spread.

For remote areas, the instruments can be removed from the truck and installed in a boat or raft if there is a water course near the project. In some wilderness areas in northern Maine, the equipment may be adapted for transportation by animal pack train.

PERSONNEL REQUIREMENTS

The most efficient working organization was found to be a five-man crew. The positions in the crew and their duties, with the Maine State Highway Commission classification for the personnel involved in parentheses, are as follows:

1. Interpreter (Geologist) directs the crew and makes the interpretation.
2. Instrument Operator (Radio Technician) operates the instruments, processes the paper records, directs the men handling the spread cables and maintains the equipment.
3. Shooter (Laborer II) sets the charges and moves the shooting box and associated wires.
4. Two assistants (Engineering Aide I) handle the spread cables and geophones.

ACCURACY AND COST OF THE SEISMOGRAPH TECHNIQUE

The comparison of seismic data with wash-boring and test-pit data provides a preliminary evaluation of the seismograph technique. The final evaluation is obtained from a comparison of seismic data with cross-sections that are surveyed for ledge excavation when the project is under construction. Evaluations of this type are vital steps toward the development of confidence on the part of the interpreter and toward the identification of incorrect interpretations. A comparison of seismic and wash-boring data at 51 locations is given in Table 2.

Some possible causes for the discrepancies are as follows:

1. Composition and physical characteristics of the soil vary. The seismic technique is based on uniform materials having uniform velocities, but natural soils do not possess uniform characteristics.
2. Irregular or steep bedrock surfaces tend to yield erratic data.
3. Irregular topography is found in the form of deep narrow gullies or steep hills.
4. Frost layer is more than 6 in. thick and has a higher velocity than the near-surface soils. Therefore, it acts as a "short circuit" for the shock energy and the resulting record is generally useless. The frost layer can be broken up by dynamite in the vicinity of the shot hole and, where deep frost is encountered, holes for each detector can be blasted.

TABLE 2

COMPARISON OF SEISMIC AND WASH-BORING DATA

Error (ft)	No. of Locations	Percent of Sample
0- 2.5	33	64
2.6- 5.0	9	18
5.1-10.0	7	14
> 10.1	2	4

5. Misinterpretation of seismic data is generally due to unknown subsurface conditions rather than computation errors.

The cost of a seismic survey is independent of the depth to bedrock. Therefore, the great advantage of the seismic method over conventional boring or probing methods is the saving in deep exploration. The average cost-per-depth determination of the seismic method for the period from the middle of February 1963 to the middle of August 1963 was slightly over $22. The first 2 ½ months of the period involved work in an area blanketed by 3 to 4 feet of snow. Because of the shoveling required to set up the seismic detectors the cost-per-depth determination was about $53.

The average cost of rod probings is about $1.70 per foot and the average cost of wash borings is about $5 per foot. However, a direct comparison of these costs with the cost of a seismic survey is misleading because the cost per foot of conventional methods increases with depth.

FUTURE PLANS

The seismograph system will continue to be used for centerline exploration and granular material studies, and the results will be checked with data from borings, test pits and surveyed bedrock cross-sections. Increasing use will be made of the data in the initial design stages of the highway projects. The seismograph survey is an important tool which the soils division can utilize to evaluate quickly subsurface soils information to locate the most economical highway route and grade.

More study will be devoted to areas of shallow bedrock and glacial till areas in which the data were unusually difficult to interpret. Geologic studies will continue in an effort to determine the causes of some of the large discrepancies found between the seismic depths and the true depths.

A study of sources of energy other than dynamite is planned. One example is the common 8-lb sledge struck against a steel plate on the ground, such as used with the single-channel counter system.

CONCLUSIONS

The quality of the results obtained with the seismograph justifies the expense involved in its purchase and operation. The efficiency and speed with which information can be gathered has resulted in the elimination of many probings and the more efficient scheduling of borings. Confidence has developed among the engineers using the data and the future is a bright one for the seismograph.

ACKNOWLEDGMENTS

We are greatly indebted to members of the Bureau of Soil Mechanics of the New York State Department of Public Works, in particular, William P. Hofmann, Principal Soils Engineer, Paul Bird and Francis R. Irving who instructed the author in field operations, methods of interpretation, and supplied graphs and data for use in calculating depths. Lawrence Wing, Geologist for the James W. Sewall Company of Old Town, provided valuable information concerning operations within the State of Maine. We are very grateful for all the assistance we received.

The author is indebted to many members of the Soils Division of the Maine State Highway Department for assistance in the preparation of this paper, especially to Frederick M. Boyce, Jr., Soils Engineer, and Ernest G. Stoeckeler, Soils Research Scientist, who offered much encouragement and constructive criticism.

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Appendix

This Appendix contains a discussion of technical details involved in the interpretation of refraction seismograph data.

After the paper record is processed and passed to the interpreter, he reads the shock wave arrival times and plots a graph of the times vs the distance from the shot hole (Fig. 2). He then draws lines on the graph to obtain the best fit between the points. The lines are called "velocity lines" because the slope of each equals the velocity at which the energy travels in the subsurface layers.

In the illustration, the V_1 line represents the low velocity of the shock wave in the soil and the V_2 line represents the path through the soil and along the high-velocity soil-bedrock interface. The shock wave travels path AD in the same time that it travels path ABCD. The distance AD, called the "critical distance," is used in determining the depth to bedrock. The velocities and critical distance, as well as the depth of the shot, are then substituted in the formula for depth (4, 5):

$$h = \frac{d}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}} + \frac{h_S}{2} \qquad (1)$$

where

h = depth to bedrock below the shot hole,
h_S = depth of the charge in the shot hole,
d = critical distance,
V_1 = soil velocity, and
V_2 = bedrock velocity.

The last three values are derived from the time-distance graph.

After a depth determination is made at hole 1, the above procedure is repeated for hole 2, and the results are referred to as a reversed profile. Then the spread is moved to the next location, generally 100 feet ahead, as shown in Figure 3. This technique is known as the continuous profile method because each hole is shot in both directions, and two depth determinations are obtained. The true depth is taken as the average of both depths. As a further refinement, in order to produce additional data and to detect irregularities in the bedrock surface, the successive spreads overlap by 50 percent of their length.

If bedrock is found at a depth of 10 feet or less below the proposed finished grade, seismic lines are run at 35 and 50 feet to the left and right of the centerline. These additional lines provide data for the ditches and backslopes and serve to verify the centerline data. The length of the spread used depends on the depth to bedrock that is encountered. If the spread is too short, the velocity line for bedrock will be missing because the critical distance will be greater than the spread length. The spread length of 200 feet is satisfactory for depths between 15 and 50 feet, but in areas where bedrock

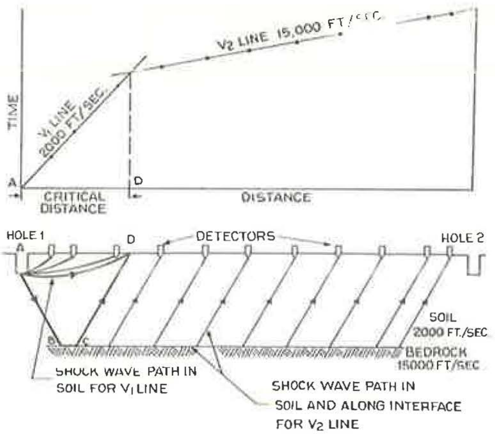

Figure 2. Seismograph time-distance graph and geologic profile.

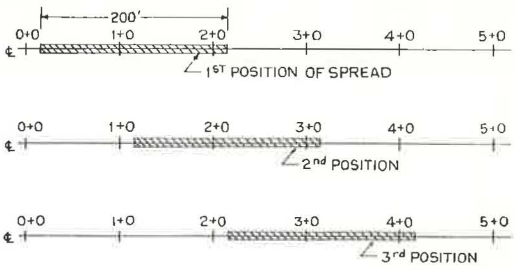

Figure 3. Successive positions of a 200-ft spread used in the continuous profile method.

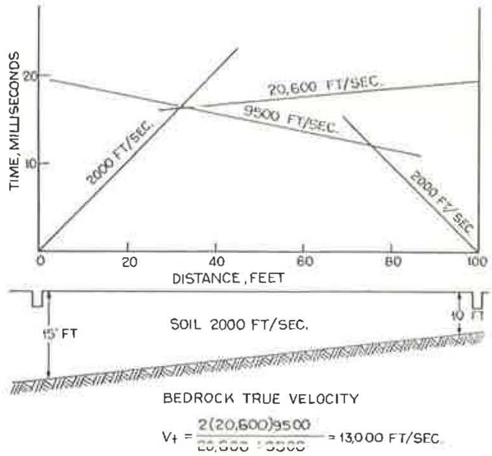

Figure 4. Time-distance graph for an inclined interface.

is deeper than 50 feet, 400-ft spreads are used. Where bedrock is about 10 feet deep or less the seismic method does not yield reliable results. This is primarily due to the extremely short critical distance and the consequent lack of V_1 control.

In the example given in Figure 2, the depth to bedrock is the same at both hole 1 and hole 2. Therefore, the bedrock velocities obtained at each hole are equal. However, if the bedrock surface is inclined with respect to the ground surface (Fig. 4), the bedrock velocity at hole 1 is much higher than at hole 2. The two velocities are called apparent velocities and are related to the true velocity by the following relationship (1):

$$V_t = \frac{2\ V_u\ V_d}{V_u + V_d} \qquad (2)$$

where

V_t = true velocity of bedrock,

V_u = up-slope velocity, and

V_d = down-slope velocity.

The true velocity, if used with discretion, can be an aid in the identification of soils materials, as discussed above.

In many areas in Maine two soil layers are found overlying bedrock. The thickness of the upper layer is calculated in the same manner as the single soil layer in Figure 2 by using Eq. 1. The thickness of the middle layer is calculated by solving the following formula, provided that sufficient velocity contrast exists between the upper and middle layers.

$$h' = \frac{d'}{2}\sqrt{\frac{V_3 - V_2}{V_3 + V_2}} + h\left(\frac{V_3\sqrt{V_2^2 - V_1^2} - V_2\sqrt{V_3^2 - V_1^2}}{V_1\sqrt{V_3^2 - V_2^2}}\right) \quad (3)$$

where

h = thickness of the upper soil layer,
h' = thickness of the middle layer,
d' = critical distance for the V_2 - V_3 interface,
V_1 = velocity of the upper soil layer,
V_2 = velocity of the middle soil layer, and
V_3 = velocity of the bedrock.

This formula is similar to the three-layer formula given by Heiland (3).

The depth from the surface to the V_2 - V_3 interface is the sum of the thicknesses of the upper soil layer and the middle soil layer:

$$D' = h + h' \quad (4)$$

where

D' = depth from the surface to the V_2 - V_3 interface,
h = thickness of the upper layer, and
h' = thickness of the middle layer.

Some Limitations of the Electrical Resistivity Apparatus

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Seven field conditions are discussed emphasizing limitations of the electrical resistivity test. In surveys to locate supplies of aggregate, the thickness of overburden, depth to underlying layer and relative cleanness of the aggregate can, singly and collectively, pose problems. Application of the test to landslide studies is limited to conditions where unlike materials exist above and below the failure zone. Some soil-rock mixtures resting on bedrock are not readily defined and soil overburden having higher resistivity than the underlying rock also produces poor test results.

The resistivity test should be limited to an expansion of subsurface data obtained by borings at structure sites. Its use in tracing aquifers may be adversely affected by the depth to the aquifer and its thickness. Natural ground currents can be so strong as to be very troublesome when using dc apparatus.

In spite of these limitations, however, it is concluded that the electrical test is a useful tool when used wisely.

•MANY WORDS have been written about electrical resistivity and its application to subsurface investigation. Most have been directed to the theory and mechanics of the operation. Some have discussed the conditions in which the apparatus has been successfully used. Few words have been written about those instances in which electrical resistivity has not produced good and reliable information. An instructor from a leading western university once asked the question, "Are there any failures in working with this type apparatus, or is it just that failures are never reported?" This paper partly answers this question and helps to fill in the apparent lack of written information on the limitations of electrical resistivity apparatus. To do this, seven situations are considered which, from experience, do not readily lend themselves to resistivity exploration.

CONSTANT DEPTH TRAVERSE IN AGGREGATE SOURCE AREAS

There are three apparent conditions that will affect the increase and/or decrease in resistance values when conducting a constant depth traverse to determine quantity and quality of granular material in an area. These conditions are: (a) thickness of overburden, (b) cleanness of the granular material, and (c) depth to a third layer underlying the granular material. The thickness of overburden will vary over a broad area. As the overburden is usually of less resistant material, an increase in thickness will result in relatively lower values of the constant depth reading, and a decrease in thickness will give the opposite results. The cleanness of the granular material likewise affects the resistance values; the more contamination, the smaller is the resistance.

The depth to a third layer can have a decided influence on resistance values. This third layer may or may not be within the depth of the constant traverse. If it is bedrock of high resistance and near enough to the surface at one test location to be included in the test depth, the resistance value will be relatively high. If the third layer is soil or other low-resistance material, the value will be relatively low.

Paper sponsored by Committee on Surveying, Mapping and Classification of Soils and presented at the 43rd Annual Meeting.

When these three conditions vary from test site to test site within the same area, they can result in many possible profiles and can be misleading to the unwary operator. A high relative resistance value does not guarantee a better aggregate area, nor does a low value necessarily denote a lesser quality aggregate area.

LANDSLIDES

Electrical resistivity has little value in locating a shear surface within homogeneous soil material. The failure that usually occurs is along an arc. The location of the failure surface has nothing to do with a changed material condition within the mass; the failure takes place along this surface because the shearing stress exceeds the shearing resistance more here than elsewhere. There is simply no condition within the material that lends itself to electrical resistivity interpretation. Failures in nonhomogeneous soils can occur along a plane of contact between two different soil layers. Often the layer on which failure occurs is itself too thin to be located by electrical resistivity methods.

Resistivity does have an application where failure occurs along a contact between two unlike materials if the difference in the resistance values of the materials is measurable and if each layer is thick enough to be evaluated.

CONTACT BETWEEN SOIL-ROCK MIXTURES AND BEDROCK

The mode of accumulation of fragmental rock and soil as a mixture on rock slopes will often result in a profile that does not offer itself readily to resistivity interpretation. Climatic and other conditions prevailing since the invasion of the Columbia basalt flows into Idaho seem to have resulted in an unusual sequence of debris accumulation on the slopes of hills and mountains. Apparently, as weathering proceeded and rockfall and rolling rock occurred on the slopes, there was little soil in the area to be incorporated with the fragmental rock as it came to rest. Therefore, the fragmental rock resting on solid rock was nearly free of soil. As time went on and the profile built up, more and more soil was available for deposit with the rock fragments. As the percentage of soil increased, the percentage of fragmental material decreased. The change was slow but constant, and there is no clear-cut change at any place in the profile. The change, as plotted from electrical resistivity reading, is so gradual that a curve results on which points of intersection are impossible to locate.

RESISTANCE OF SOIL OVERBURDEN TO ELECTRICAL CURRENT

It is unusual to find soil overburden with a resistance greater than underlying bedrock, and, therefore, it is easy to overlook this condition when interpreting the resisting values. The phenomenon was first observed on a project in northern Idaho during determination of a soils profile. The field crew had proceeded beyond the cut area and, in fact, had completed the project investigation. It was not until the overall picture was developed for the full length of the project that the discrepancy became apparent. A return trip was made to the cut and the geology of the immediate locality was studied. There seemed to be little question that the layer beneath the overburden had to be rock. A drill was brought to the site and a boring was made which verified rock as the second layer.

The most unusual feature was that tests made by electrical resistivity in adjacent cut areas involving the identical rock formation showed that the overburden was of lesser resistance, although it appeared to be of the same composition as the overburden which gave the higher values. We still have not accounted for the discrepancy to our satisfaction. This situation points out the need for study of local geological conditions along with electrical resistivity investigation.

FOUNDATION INVESTIGATION FOR STRUCTURES

Not much needs be written on this subject as the limitations inherent in use of the electrical resistivity method for this purpose are readily apparent. It is not enough to supply only a log of the profile to a structure designer; strength data must be obtained adequately to design the footings and substructure. Also, the changes in formation cannot be located closely enough by the resistivity method, and a few tenths of a foot can be very significant.

We do not wish to convey the impression that resistivity data should not be considered of value at structure sites. It is of value, but should be used only as a supplement to drill-hole logs.

TRACING AQUIFERS

The success in locating aquifers by this method depends on the thickness of the aquifer and on a measurable difference in the current resistance of the aquifer and the material above and below. Many aquifers are too thin to project a measurable change to the plotted curves. It is only when the aquifer is reasonably thick (i.e., two feet or more) that it can be located with any certainty, assuming that there must be two points at least on the plot to locate an aquifer. If an aquifer is only several feet thick, the electrode spacing must be shortened. If the resistance value of the material above the aquifer is close to that of the aquifer, it may be impossible to locate the contact. Likewise, if the same condition exists with the material below the aquifer, it may be impossible to locate the lower contact. As it is important to determine the thickness of the aquifer, as well as its surface position, these variable situations can result in a confusing picture.

GROUND CURRENTS

This phenomenon is not restricted to buried cables, substations, and high-voltage lines in the area investigated. Ground currents of appreciable magnitude may exist where there are no man-made electrical installations. Not only do unexplained ground currents exist, but also they do not express any directional pattern consistency.

We have experienced ground-current phenomena in which the direction of flow changes at depth. With one reading the currents are moving in one direction and perhaps two readings later, at only six-feet lower elevation, they are in an opposite direction. If there were any practical reason, I believe that their course could be plotted at different levels beneath the surface.

It has been possible on some, but not all, occasions to overcome this condition with the battery capacity we have. I suppose that resistivity equipment that can withstand a heavier current load theoretically could overcome these ground currents. Where the total battery supply has been able to overcome these currents and still be measurable, the results of the tests appear to be reliable. Change of traverse direction has also been somewhat successful.

SEISMIC APPLICATION

This paper would not be complete without a short discussion on the compatibility of seismic equipment with electrical resistivity. One can supplement the other rather neatly in some situations where each by itself would not produce reliable information.

A refraction seismic apparatus has the distinction of plotting the subsurface through changes in sound-wave velocity caused by variable densities of different materials. A plot of the profile, to be accurate, requires that the subsurface materials express these different velocities through an increase in their respective densities with increase in depth. That is, the second layer must have a greater velocity than the first to establish the contact and a third must have a greater velocity than the second. If the first layer has a greater velocity than the second, a contact cannot be established.

The use of one method to supplement the other can be readily seen. When the contact between soil and rock mixtures and bedrock could not be determined with resistivity, the refraction seismic method proved suitable for the task. A condition where high velocity cap rock overlies lower velocity soil material is not suitable to refraction seismic interpretation but may readily succumb to electrical resistivity.

CONCLUSIONS

Electrical resistivity can be a useful tool, but only if one realizes the limitations. When they are kept in mind, many of them can be coped with, or compensated for, by other aids.

One such aid has been discussed in this paper; others are available. There are six electrical resistivity systems currently in operation in Idaho. Their value has far exceeded any drawbacks they may have. I would judge that without them and their ease of transportation to an investigation site, there would be instances where no other investigation would have been made because of inaccessibility to other equipment.

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.

Paper sponsored by Committee on Surveying, Mapping and Classification of Soils and presented at the 43rd Annual Meeting.

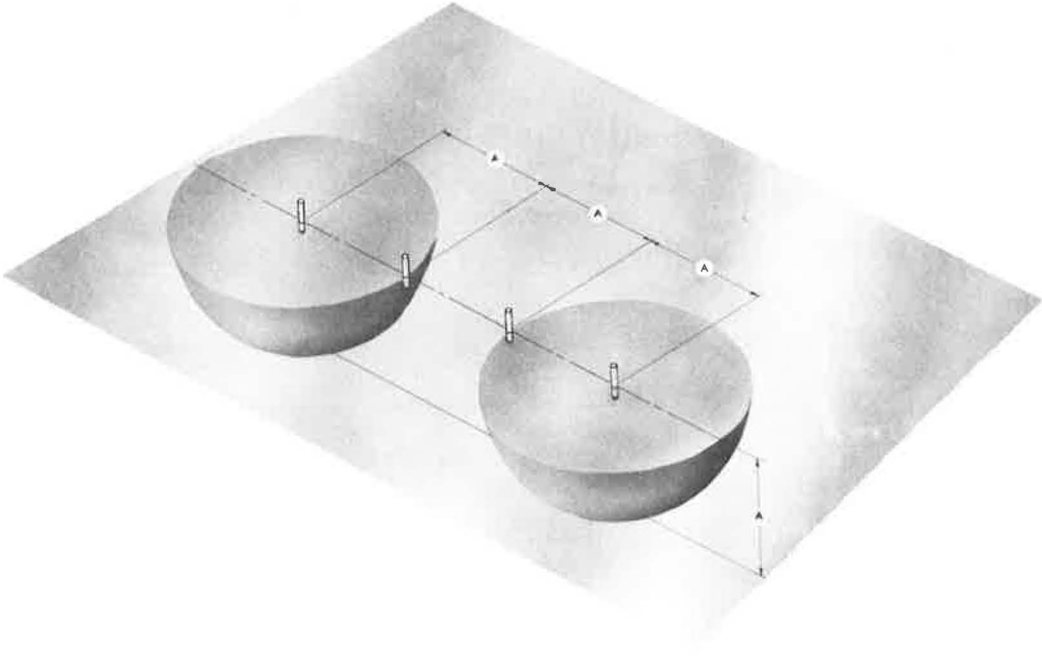


Figure 1. Soil mass measured by "potential bowl" theory.

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

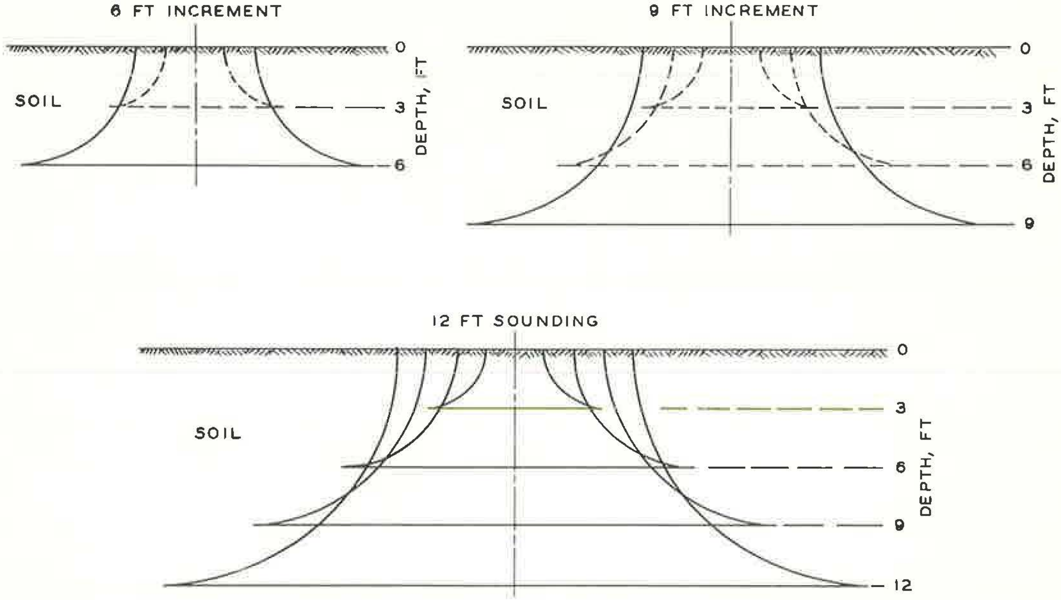


Figure 2. Development of resistivity soundings by increments.

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.

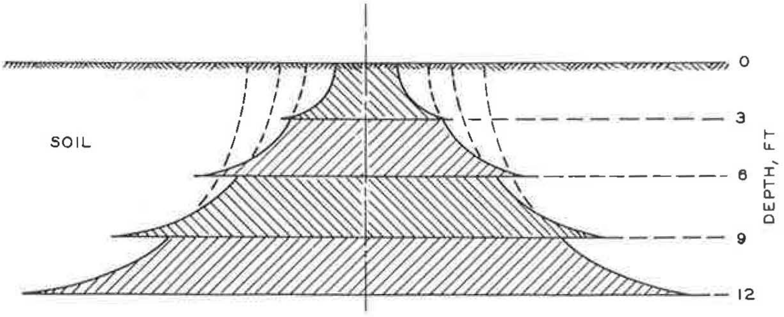


Figure 3. Resistivity of individual layers by increments of depth.

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):

$$\frac{1}{R_n} = \frac{1}{\bar{R}_n} - \frac{1}{\bar{R}_{n-1}} \qquad (2)$$

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.

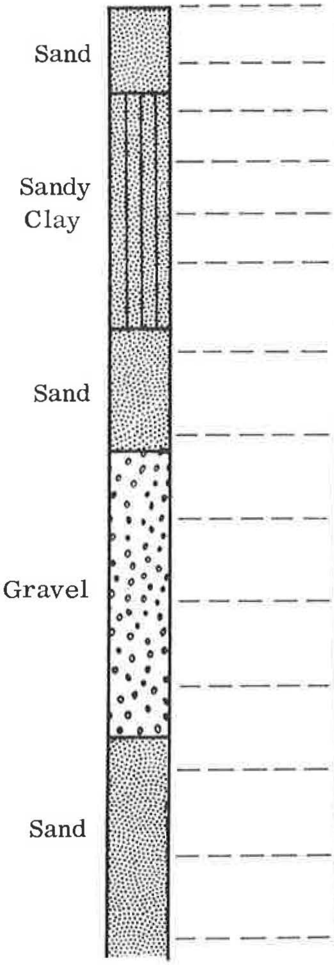
Resistivity layer values are interpreted by comparing the electrical logs to index correlation borings. It is generally found that the major textural soil classes such as clay and sandy clay, loamy sand, sand, and gravel will fall into definable ranges of resistivity values which are usually constant 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

Correlation Boring



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

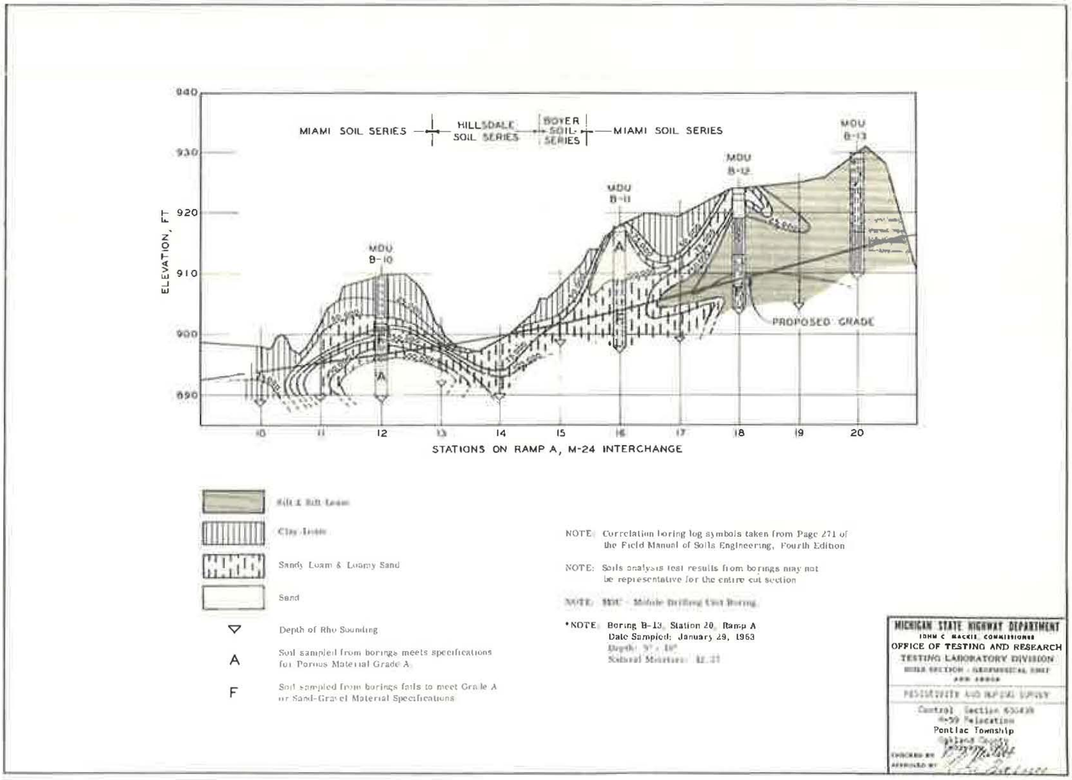


Figure 4. Cross-section from resistivity profile contours.

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-

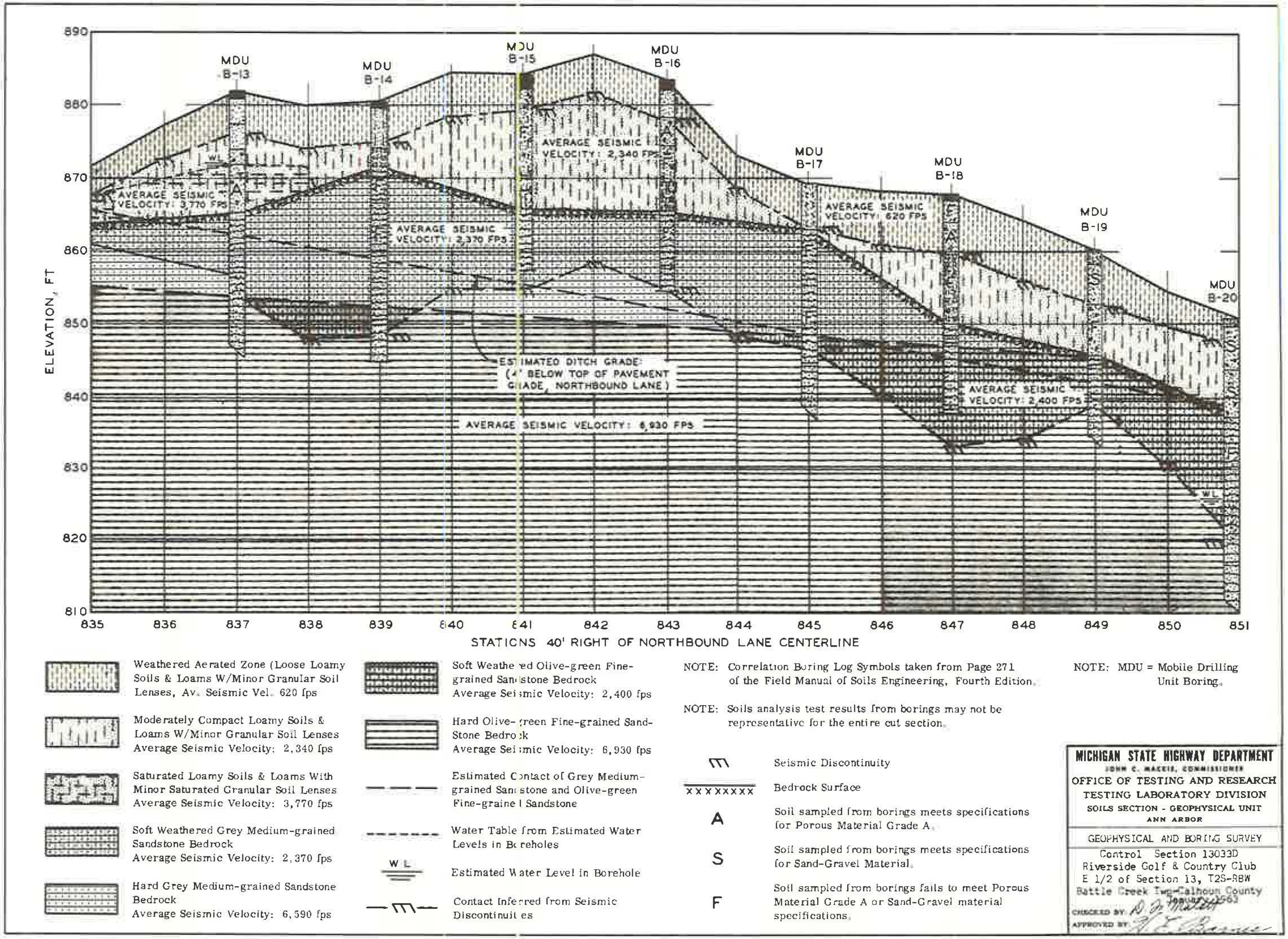


Figure 7. Cross-section from seismic discontinuities and borings.

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.

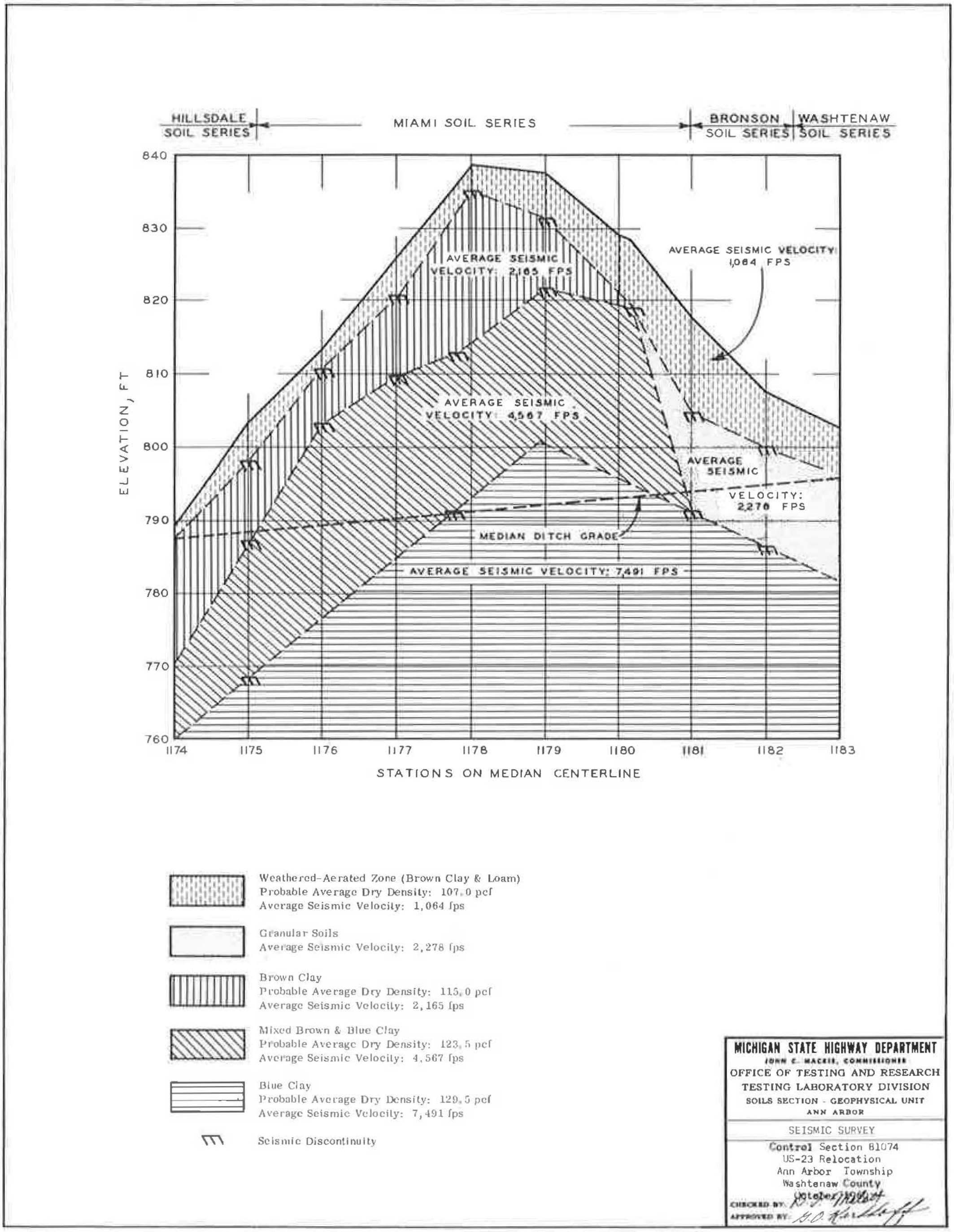


Figure 9. Cross-section from seismic discontinuities showing zones of increasing density and seismic velocity in clayey glacial drift.

Figure 10. Seismic truck.

Figure 11. Explosives handler with seismic charge.

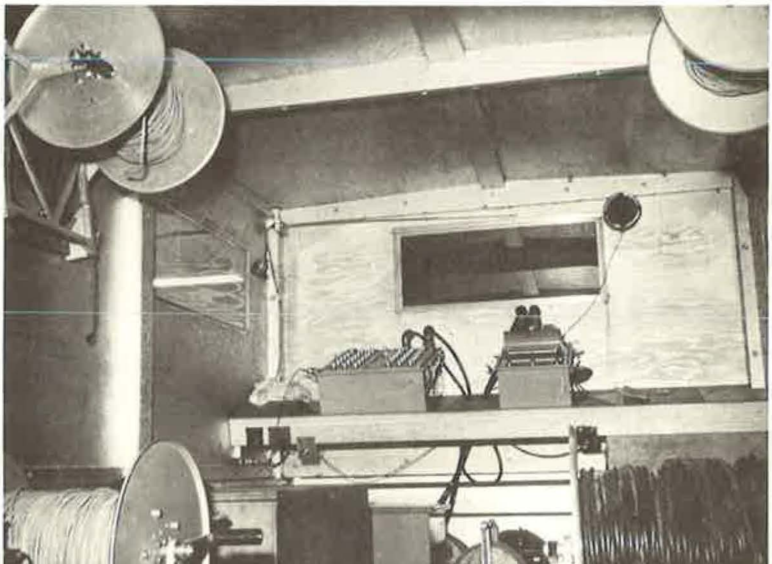


Figure 12. General view inside seismic truck showing Electro-Technical Labs 12-trace seismograph and reels of seismic wire.

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.

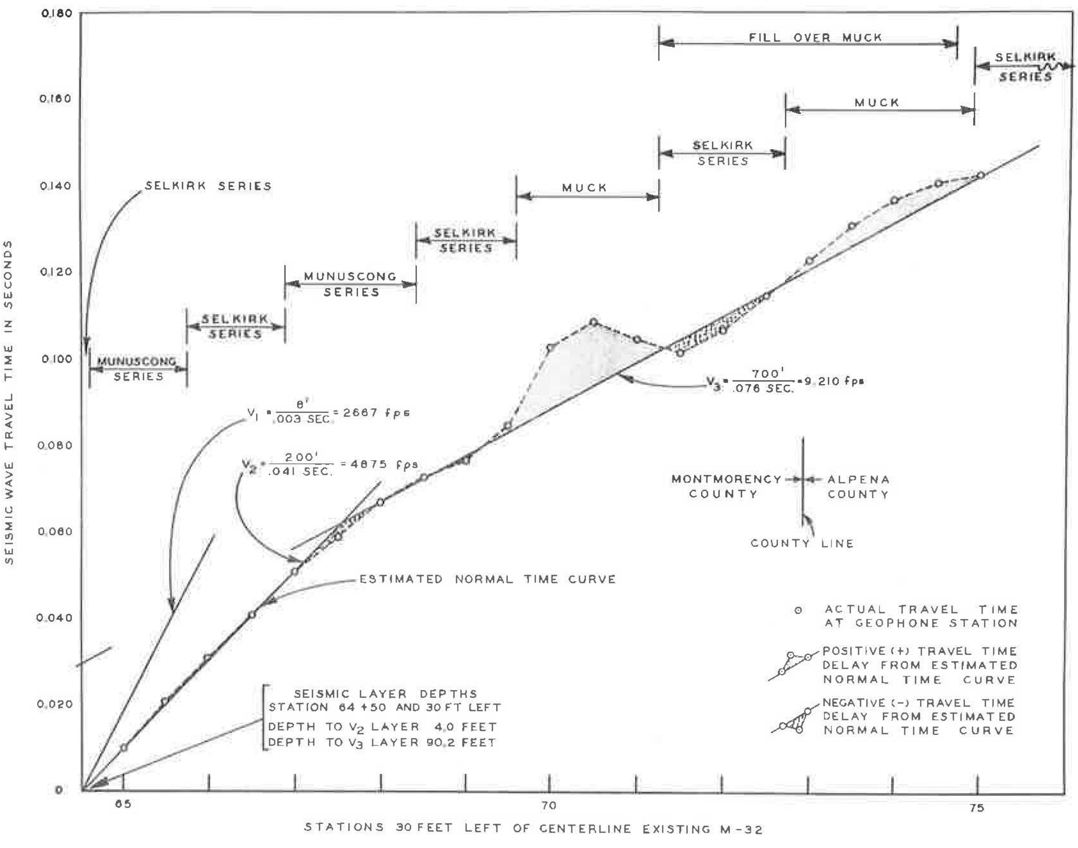


Figure 13. Refraction seismic profiles in relation to pedologic soils mapping.

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

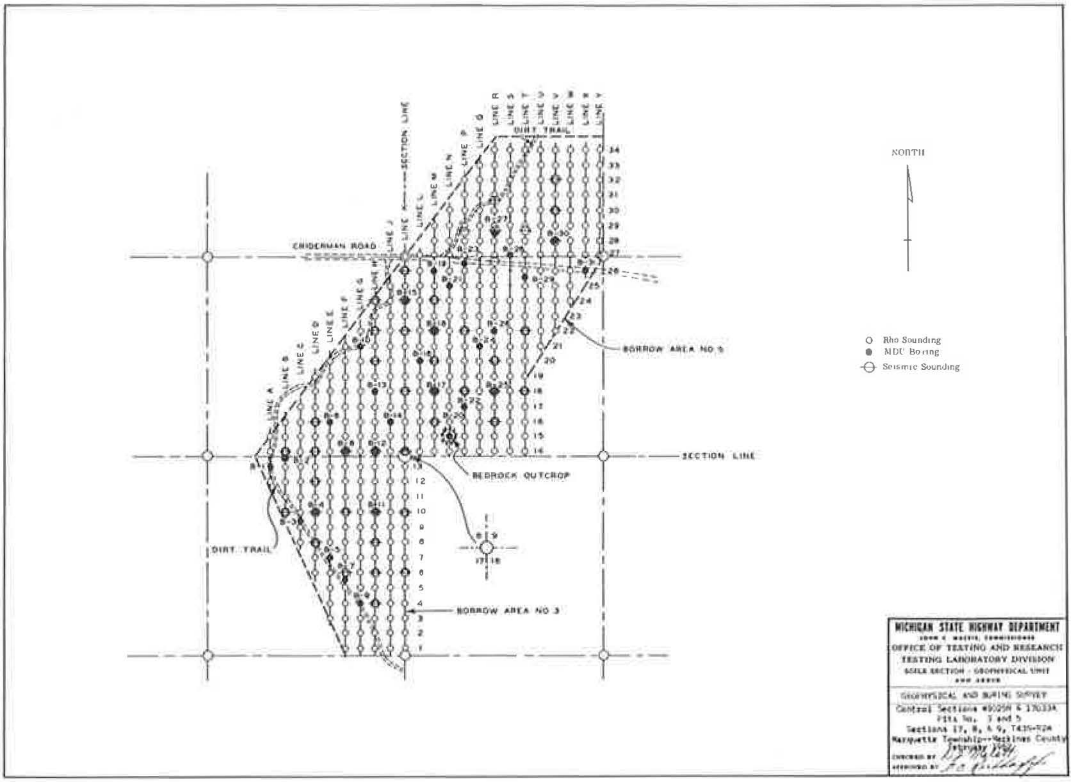


Figure 14. Borrow pit general location plan of resistivity and seismic survey.

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.

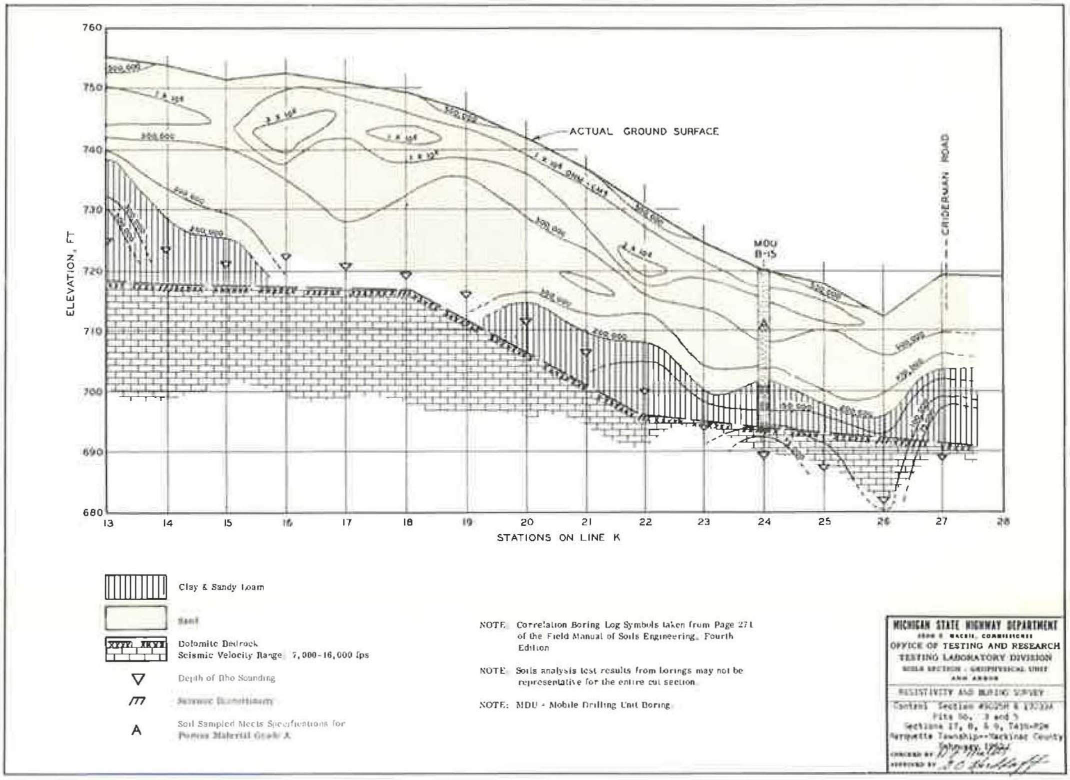


Figure 15. Cross-section from profile contours and seismic discontinuities.

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

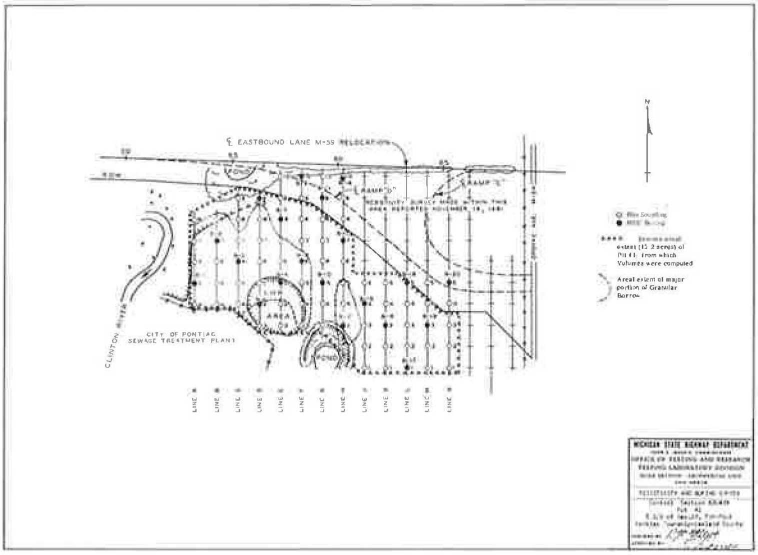


Figure 16. Borrow pit general location plan of resistivity survey.

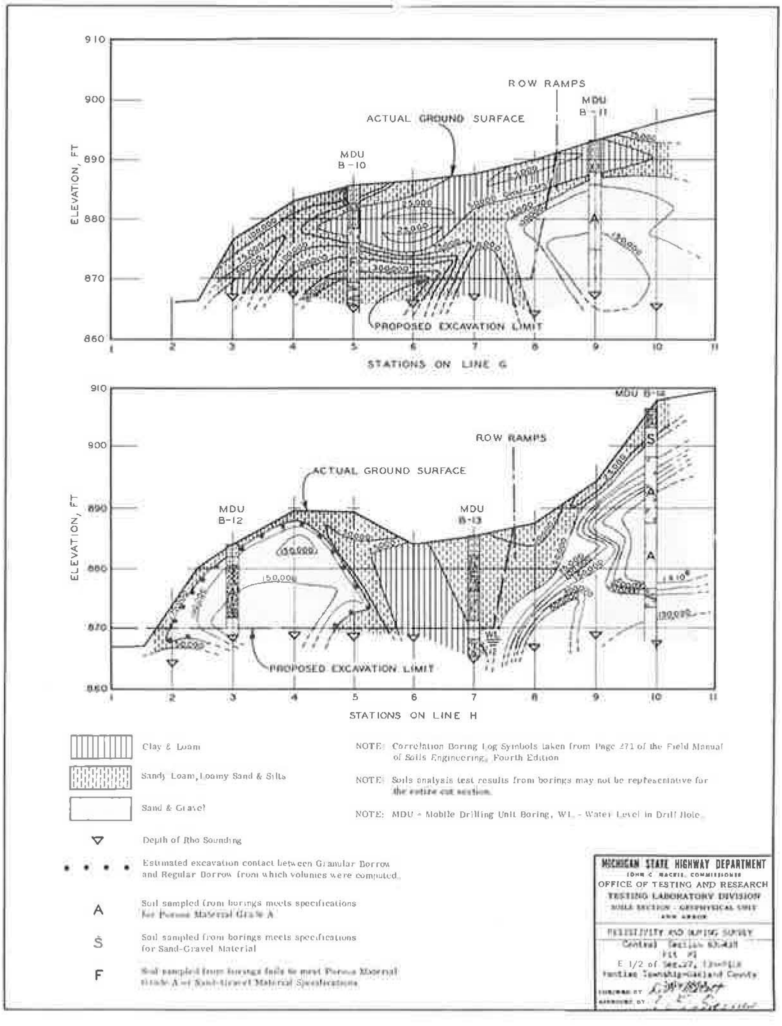


Figure 17. Cross-sections from resistivity profile contours.

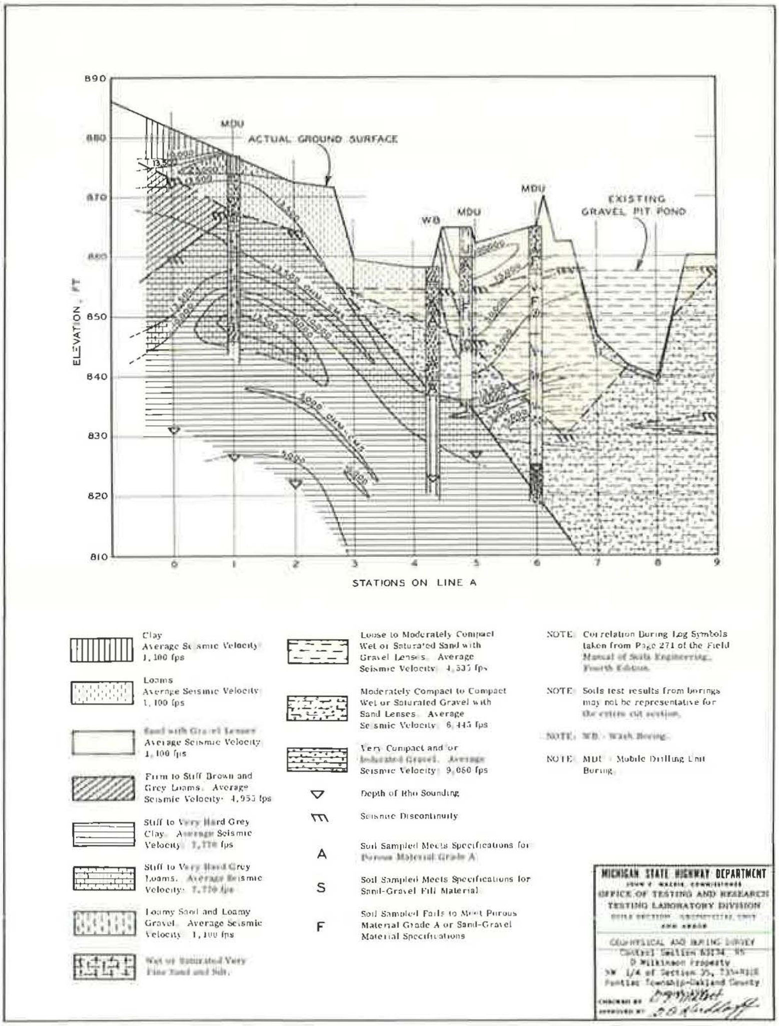


Figure 18. Cross-section from profile contours, seismic discontinuities, and borings of an underwater borrow pit.

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

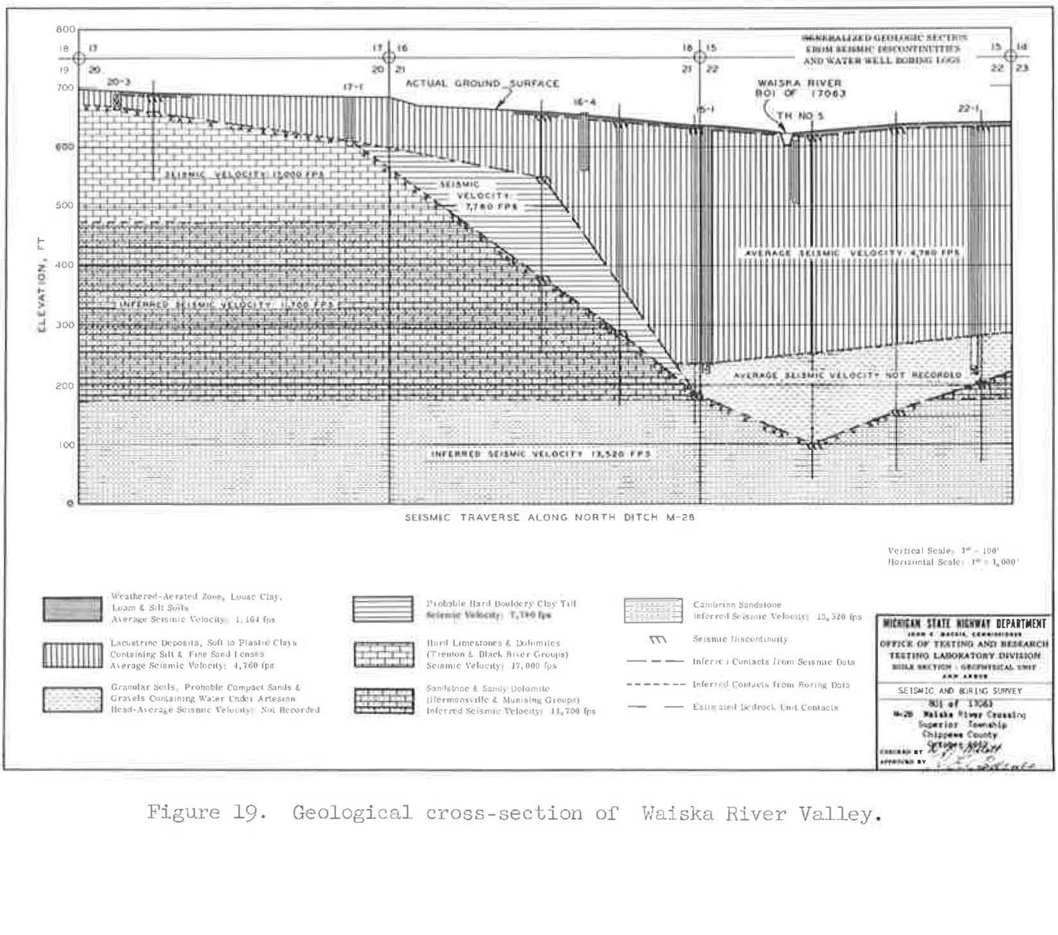


Figure 19. Geological cross-section of Waiska River Valley.

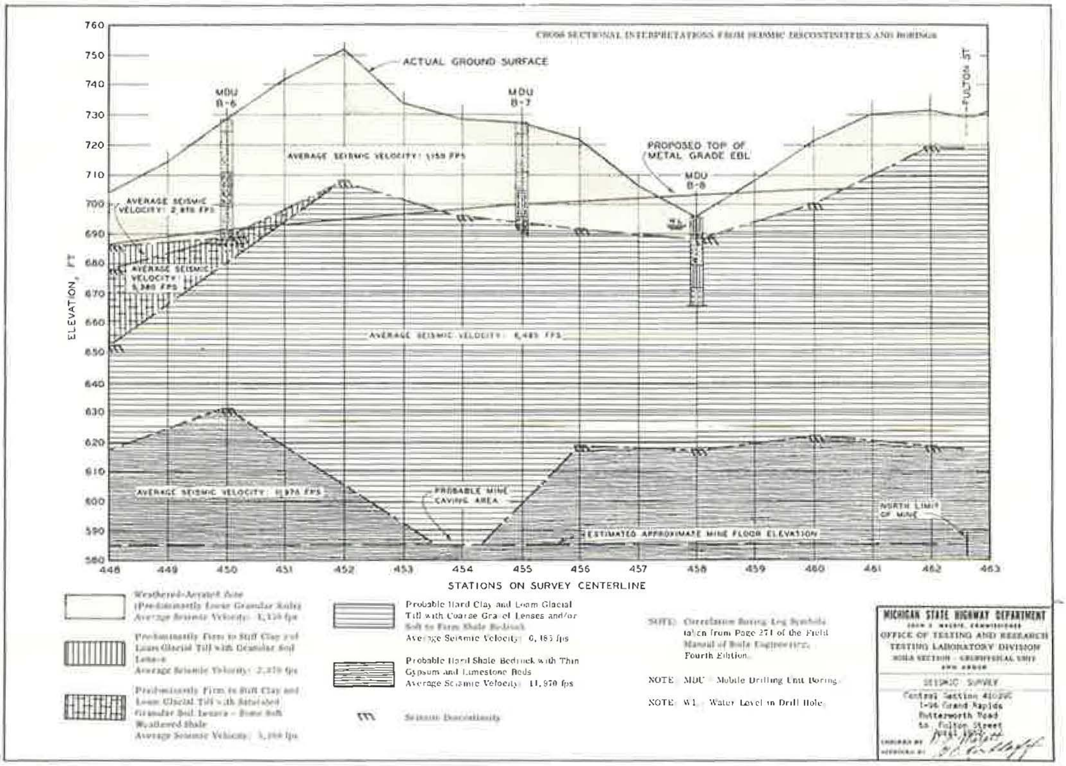


Figure 20. Seismic and boring cross-section showing bedrock and probable mine caving zone.

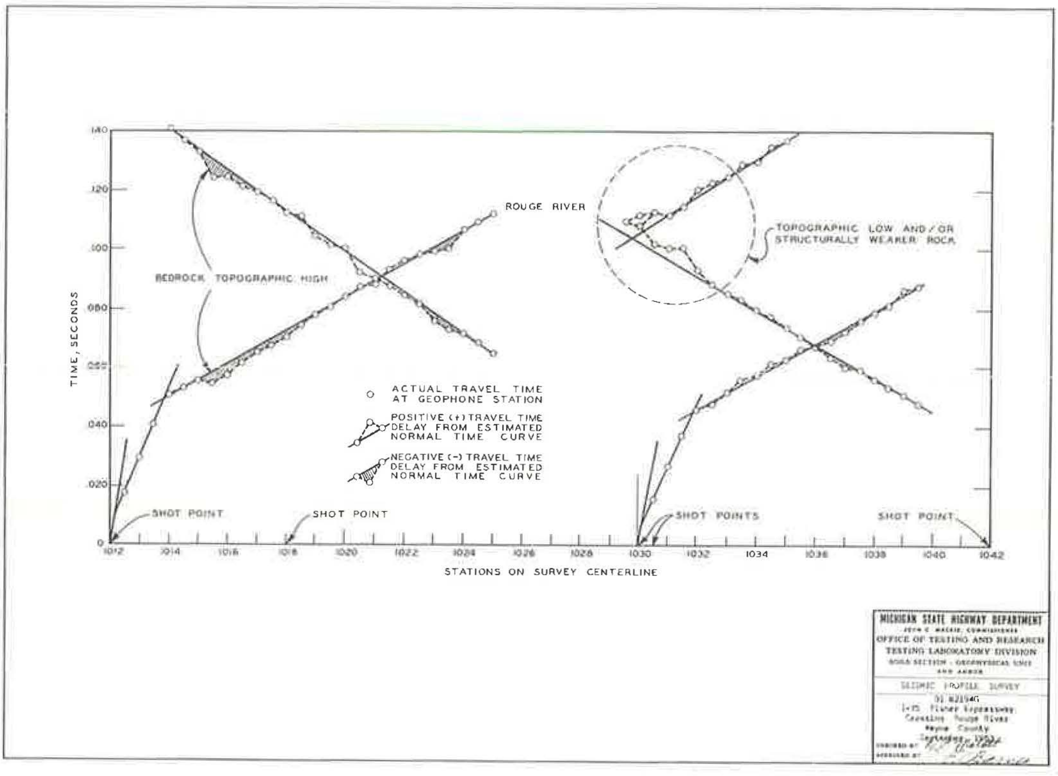


Figure 21. Time-distance chart of seismic profile survey for Rouge River crossing.

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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Geophysical Equipment Usage in the Wisconsin Highway Commission Organization

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Respectively, present Soils Engineer, Warzyn Engineering & Service Company, Madison, Wisconsin; former Central Office Soils Engineer, State Highway Commission of Wisconsin; Assistant Soils Engineer, and Geophysicist, State Highway Commission of Wisconsin

The use of geophysical equipment by the State Highway Commission of Wisconsin is a relatively recent endeavor. With the exception of a few limited geophysical surveys made prior to World War II using a pioneer model resistivity apparatus, all comprehensive surveys have been made within the past three years.

The geophysical program presently employs one electrical resistivity apparatus and one single-channel refractive seismograph. In general, the combined use of two types of instruments provides more conclusive subsurface information. However, the inherent limitations of either method may restrict the use of one instrument or the other to a certain geological province.

The primary purpose of the geophysical program is to provide maximum subsurface information at the lowest possible cost. Realization of this objective has resulted in a reduction, in certain instances, of the number of hand and machine test borings necessary to supply the required subsurface information.

•GEOPHYSICAL SUBSURFACE exploration methods now in use in the Wisconsin Highway Commission are in an experimental stage with the main objective being to provide a maximum of generalized subsurface information at minimum cost.

The tools used by our geophysical unit are a resistivity apparatus and a single-channel refractive seismic instrument, each of which is a light-weight, self-powered, compact device. These tools are employed primarily to confirm the existence of and depth to bedrock in cut sections, and the probable degree of rippability of the bedrock. Other uses include determining the presence and extent of potential frost heave soils and the location and limits of potential aggregate deposits.

A resistivity device was built according to pioneer BPR plans in 1937 and used intermittently until the program was dropped during World War II. The results of that work are not clear-cut. In some areas results were good, but in others the device was not dependable. Resistivity work was not resumed until 1960, when new equipment was purchased and a full-time geophysical crew began operations on a statewide basis. The findings resulting from their various projects are described in the following report.

It is emphasized that we do not have all the answers by any means, and have much yet to learn. It has been found, however, that the use of these geophysical instruments can yield a large amount of generalized subsoil information, provided that the work is supervised by an experienced geophysicist who is cognizant of the local geology.

Currently, the geophysical unit is under the direction of a graduate geologist. The unit is a subdivision of the Soils Unit, Central Office Materials Section. All geophysical work is conducted by this subdivision on request from individual district offices. The results of the survey are sent directly to the parties requesting the investigation.

Paper sponsored by Committee on Surveying, Mapping and Classification of Soils and presented at the 43rd Annual Meeting.

GEOPHYSICAL EQUIPMENT IN USE

In view of the extensive amount of literature available from equipment manufacturers, only a general description of the equipment in use is presented here.

The resistivity apparatus used is a model 274M Michimo from Associated Research, Inc. Figure 1 shows the equipment as set up to take readings. Some of the accessories included are of our own manufacture. Both the Barnes Layer method (1) and the cumulative method (2) of resistivity plotting have been used with nearly equal results. The Barnes method, however, has proved to be more convenient.

Procedures followed in performing resistivity surveys are not completely standardized. Much depends on the geology of the site and the type of information needed. In general, procedures used follow the practices of other states and equipment users who have reported on the subject in miscellaneous publications.

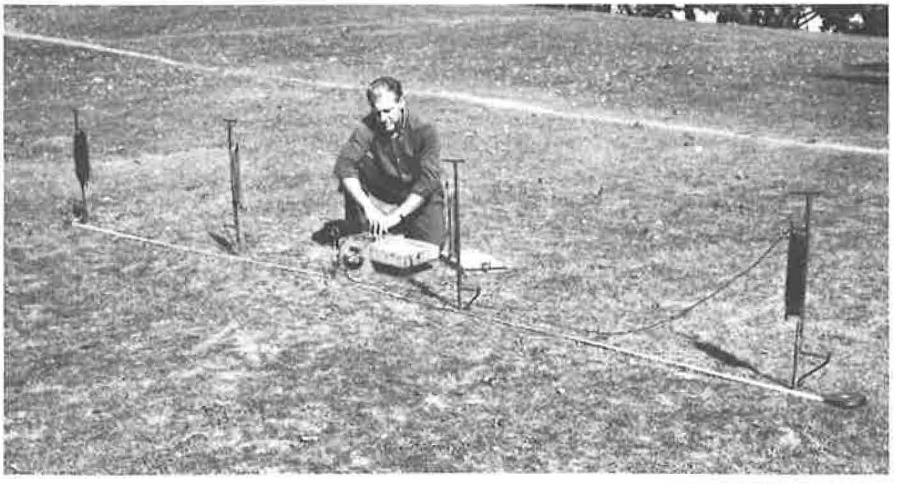

Figure 1. Resistivity instrument as set up to take readings.

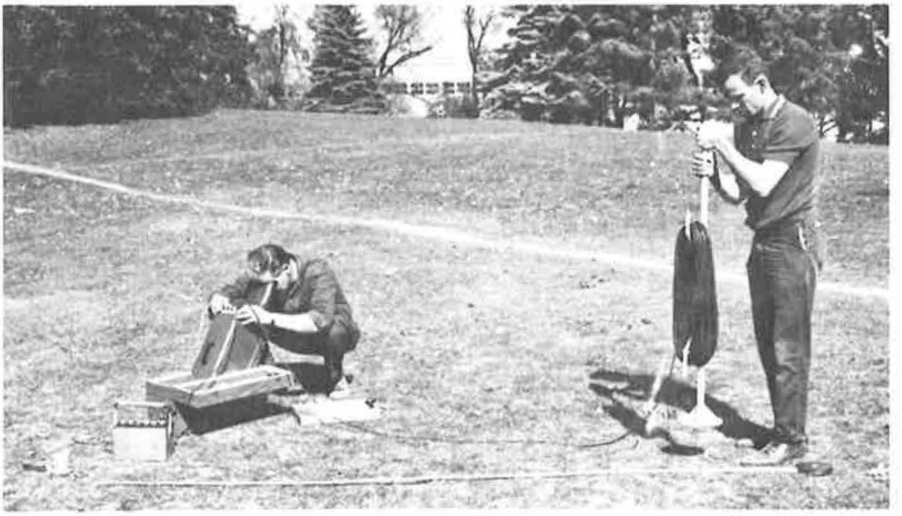

Figure 2. Seismic instrument as set up to take readings.

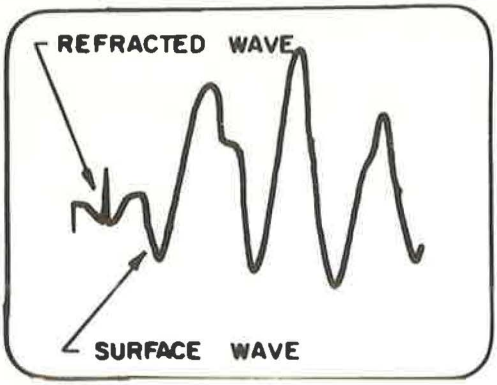

Figure 3. Typical waveform as observed in the oscilloscope of the seismic instrument; the marker is observed in the first trough of the waveform.

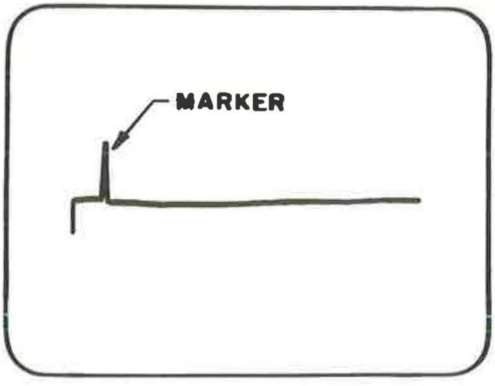

Figure 4. Straight line waveform illustrating the marker.

TABLE 1

MERITS AND LIMITATIONS OF RESISTIVITY AND SEISMIC APPARATUS[1]

Qualification	Resistivity	Seismic
1. Locates bedrock surface	Usually	Yes
2. Distinguishes between hard and soft sandstones	No	Yes
3. Detects soft layers beneath hard layers	Usually	No
4. Is affected by wind, traffic, etc.	No	Yes
5. Is affected by fences, buried cables, and overhead wires	Sometimes	Seldom
6. Differentiates boulder zones from bedrock	Usually	Usually
7. Locates water table		
(a) In soil	With difficulty	Usually
(b) In rock	Yes	Very difficult
8. Aids in determining rippability of bedrock	No	Yes
9. Usable in water saturated areas	Yes	No
10. Usable in frozen ground	Yes	No
11. Operates under wet or damp conditions	Yes	No
12. Locates suitable quarry rock	Possible[2]	Yes[2]
13. Locates suitable gravel deposits	Yes[2]	Sometimes[2]
14. Affected by uneven ground surface and uneven subsurface layers	Yes	Yes
15. Requires experienced operator	Definitely	Definitely

[1]Equipment discussed is Model 274M Michimo Resistivity Apparatus and an early model Terra-Scout seismograph. The limitations discussed herein pertain only to this equipment.
[2]Based on very limited experience.

The seismic unit in use is an early model Terra-Scout, a portable, single-channel seismograph. An improved model is presently marketed by Soiltest, Inc. Both models employ an oscilloscope to provide a replica of the sound waveform and to assist in timing the sound waves initiated by blows to the earth with a tamper. Figure 2 shows the seismic equipment as set up to take readings. Figure 3 shows a typical waveform as observed in the oscilloscope by the operator. The marker indicated in Figure 4 can be observed in Figure 3 at the first trough of the waveform when the operator has the instrument properly adjusted for a reading.

COMPLEMENTARY USAGE OF RESISTIVITY APPARATUS AND SEISMOGRAPH

In the last two years of operation, Wisconsin's geophysical unit has come to the conclusion that efficient use of available geophysical equipment in a manner to give conclusive subsurface data can be accomplished only when the operator understands the merits and limitations of each instrument. These merits and limitations, in addition to recognition of local geological details by an experienced operator, aid in selecting the instrument best suited for the intended purpose. Table 1 lists the various features of each geophysical method which should be considered in selecting complementary equipment, and indicates some of the advantages of such complementary usage for highway engineering subsurface investigations.

ADVANTAGES IN USING GEOPHYSICAL EQUIPMENT

Savings in cost result when geophysical instruments are employed in a carefully organized program of subsurface exploration in the preliminary stages of highway design. Geophysical methods provide generalized rather than specific information concerning the subsoils as contrasted to information obtained from borings. Geophysical data are usually verified by a few selected borings at each cut, and in this way provide the broad area coverage that could otherwise be obtained only by making many borings at a much higher cost.

Broad areal coverage saves time as well as money. Subsurface information can be obtained much faster by geophysical methods than by conventional methods of power or hand borings, and, in addition, the portability of the equipment permits rapid investigation of large areas.

Geophysical methods can be used to advantage as a preliminary to the planning and organizing of a boring program. Specific boring locations can be selected with greater accuracy by using generalized pictures of subsurface conditions obtained from preliminary work.

To summarize, from the standpoint of cost and speed of operations, geophysical methods far outrank other subsurface investigation methods normally used in our highway planning program.

DISADVANTAGES IN USING GEOPHYSICAL EQUIPMENT

Current policy requires that the geophysicist be thoroughly experienced in operating equipment and in interpreting data inasmuch as years of experience appear to be needed before an operator can interpret with some degree of confidence all of the data all of the time. Therefore, the geophysical instruments should not be used by different survey parties on an intermittent basis. In addition, the operator must have a working knowledge of geology. These limitations may be considered a disadvantage in the use of this type of equipment.

Due partially to Wisconsin's inexperience and partially to the inherent limitations of our geophysical methods and equipment, it is not possible for our geophysicist to interpret with confidence all data obtained. When major subsurface differentials (such as till overlying hard bedrock) are present, the interpretations are easily made and the results are quite dependable. On the other hand, when subsurface differentials are minor or inverted and contain silt pockets, wet layers, irregular weathered zones, or boulders, interpretations are difficult to make and the results rather undependable. Perhaps with added experience, confidence and accuracy will improve.

A disadvantage found occasionally when using geophysical instruments is the disturbing effect of cultural features, independent of geology, on geophysical data. Some of these effects are caused by overhead wires, metal fences, embankments or trenches, buried utilities, and the noises created by traffic and wind. These effects are seldom encountered but they are mentioned because they can interfere with operations, particularly in urban areas.

Finally, problems develop from breakdowns within the equipment itself. As with all electrical and electronic instruments, short circuits and tube failures will occur. Most of the troubles experienced in this respect have been electrical in nature with breakage of the lead wires or contacts common in the resistivity instrument, and slight electrical leakage shorting out the hammer circuit of the seismic instrument. Either of these items can decommission the instruments rather easily, and, although annoying at the time, are considered to be a minor disadvantage in that they seldom interfere with the overall performance of the geophysical unit.

TYPICAL ROAD CUT INVESTIGATION PROCEDURE

In Wisconsin each major road cut on planned highway projects is investigated by one method or another to determine the kind of material within the excavation limits. Most deep cuts are investigated by geophysical means together with a few selected borings. These deep-cut investigations are conducted to confirm the presence or absence of bedrock in the cut so that the excavation bid item can be properly designated. Also, as mentioned earlier, secondary features such as the location of silt pockets or seepage zones may also be investigated.

The geophysical phase of cut investigations consists of several parts. Initially, the area under investigation is studied in the office by the geologist, making use of geologic reports and maps, aerial photographs, well logs, and pedologic information to prepare a preliminary geologic report on the site. The geophysicist then lays out the field program, taking into consideration the advantages and limitations of the instruments in relation to local geology and the project requirements.

The field work is not standardized into a routine performance using a grid system or uniform spacing of geophysical soundings, but rather, is performed as the geologic features and project requirements dictate. For instance, when confirmation of the presence or absence of bedrock in proposed cut sections is required in an area of morainal ridge country with no known bedrock occurrences, only a minimum of geophysical work is needed. In an area of similar topography with known exposures and occurrences of bedrock, a more extensive geophysical investigation is necessary not only to determine the presence of bedrock but also to delineate contours of the rock surface.

Whenever possible in the initial stage of a project investigation, the geophysical apparatus should be operated over known subsurface conditions near the project location to provide data with which the project readings can be correlated. The known subsurface conditions may consist of outcrops, road cuts, previous borings, or well records.

A geophysical report including all the seismic and resistivity data, a brief description of the general geology, a summary of design recommendations, and any suggestions for locations of check borings, is prepared for the District Office requesting the survey. The report may be used as an aid in pedologic mapping, in making recommendations to the design section, or in any other specialized use as indicated in the survey request.

Most geophysical investigations in Wisconsin to date have been in proposed road cuts. However, a limited amount of work has included investigations concerning the depth of marsh deposits, the location of potential landslide slippage planes, potential sources of aggregates, sewer trench rock quantities, and dam foundation studies. Some work on the prediction of probable bedrock rippability has been completed, but no conclusive results are available yet.

ACCURACY OF GEOPHYSICAL METHODS

Because our recent geophysical experience dates back only three years, the number of previously investigated sites exposed by construction is quite small. Therefore, opportunities for checks on predicted subsurface conditions have been quite limited. However, on work which has been completed, it has been determined that the presence or absence of bedrock was correctly established in nearly all cases. The actual depth to bedrock was found to be within a few feet of the predicted depth in about 90 percent of the cases. In those instances where the anticipated depth varied by several feet, the rock surface was found to be irregularly weathered and quite uneven. No positive information is on hand to verify the accuracy of geophysical interpretations with regard to secondary features such as ground water elevations or silt zones.

At this time the range of accuracy to be expected from any particular geophysical investigation cannot be stated with confidence, but in general it appears that work accuracy is rather closely connected to the regional geology. By this is meant that certain geologic areas of the state are more conducive to geophysical methods than other areas. It would be expected, therefore, that accuracy will vary with the region investigated. Presently, there is too little data in this field to permit a more informative statement.

COST OF GEOPHYSICAL INVESTIGATIONS

In the early stages of any experimental program, developmental and research costs constitute a considerable proportion of total cost. Considering these expenditures, the cost for geophysical surveys has ranged between \$0.50 and \$1.50 per foot of depth investigated. Now that many of the preliminary programs are completed, this cost is expected to drop considerably.

CONCLUSIONS

It is emphasized that the statements in this paper are based on a limited amount of experience and must be interpreted in that light. It is encouraging that the use of geophysical methods in Wisconsin has proved rather successful. The cost factor also appears to be improving.

The experience in Wisconsin has shown the importance of obtaining geologic information during the planning of a geophysical exploration program. It has also brought out the merits and limitations of the various types of geophysical equipment presently owned by our department. Needless to say, experienced operators are a primary requirement if valid and economical results are to be obtained.

When properly supervised and intelligently planned, geophysical investigations for highway engineering purposes result in significant cost savings and provide a large amount of useful highway design and construction information.

Discussion

STEPHEN V. THOMPSON, Soiltest Inc.—Geophysical equipment has come into wide use for subsurface soil investigations in recent years. Much work has been done with seismic and resistivity instruments to complement conventional sample boring and test holes. Since relatively few papers have been presented in the technical literature, the authors are to be complimented for presenting information on operating characteristics of the types of instruments frequently used in this type of geophysical work.

The growing acceptance of geophysical investigation techniques has been helped by the relatively low cost of this type of investigation, the speed at which large areas may be covered, and the fact that investigations may be carried on in terrain which may be inaccessible to conventional drilling and sampling equipment.

Information obtained using geophysical methods is best utilized by comparing it with information obtained from actual test borings for correlation and check of the geophysical data. Also, geophysical techniques can help in the intelligent location of the actual test borings.

With use, operators of geophysical subsurface exploration instruments are finding more applications. For example, water table elevations can be determined over an entire site. Some highway departments have used the refraction seismograph for location of caves, limestone potholes and other subsurface openings which would affect the location of a highway route. Highway departments and quarry operators are using the new techniques for rapid and low cost location and evaluation of sand, gravel and stone deposits.

The authors place emphasis on the necessity of having highly qualified personnel operating geophysical equipment. This, of course, is desirable but it is difficult to find men who are so thoroughly qualified. Experience comes with use, and electronic equipment for subsurface exploration has found wide acceptance only recently. Engineers and technicians who have a knowledge of the subsurface soil in the areas in which they operate, can, with a relatively short period of training, do an effective job using the geophysical testing techniques. In some instances, only a few hours of training time has been required to equip personnel with enough information to operate the devices. Routine geologic and soil conditions can be evaluated by operators with a moderate amount of special training. Since most projects involve correlation with sampled borings, the geophysical data can be checked against actual samples. Interpretation of basic data and planning the field techniques, naturally, require additional experience and training.

When unusual geological conditions exist, even sampled boring methods can rarely be expected to give a complete picture of subsoil conditions. At best, a boring will give an indication of the material in the immediately adjacent area. These borings, when correlated with geophysical data will give a much broader picture and confirm the continuation or discontinuation of a stratum or condition. Thus, a boring program supplemented by geophysical exploration (or vice versa) leads to a more detailed soil profile without necessarily increasing the cost of the investigation and, in many cases, actually decreasing the overall cost.

To illustrate the effectiveness of the refraction seismograph subsurface exploration technique, Soiltest, Inc., has conducted demonstrations in 14 different countries. In most cases, the operator conducts the demonstrations without any previous knowledge of the subsurface conditions. It is requested that those arranging for the demonstration site have available data from borings which can be used for correlation and check once the geophysical subsurface exploration information has been developed. The degree of accuracy that can be obtained using the seismograph or the resistivity units, is, of course, dependent on the type of subsurface material encountered, the skill of the operator, operating conditions and the amount of geological information available for the area.

The authors present data on the cost of geophysical investigations. The basis of determination of cost is not defined and could be misleading. Actually, one traverse using geophysical methods can take the place of a number of borings to the complete depth. By using a cross-section grid, a complete area may be evaluated and subsurface data plotted. It would be difficult to assess the cost on the basis of so much per foot of depth investigated. The area covered should be related to the cost. Like sampled borings, the cost is also dependent on the type of materials encountered.

Borings and geophysical work should be correlated and complement each other, and it is unwise to attempt a comparison of cost on a per foot basis.

The very nature of the geophysical method makes it possible to cover a much wider area at less cost in less time. The data should be correlated to borings worked into the same exploration program.

Status of Published Soil Surveys October 1, 1964

The following tabulation lists the counties and other areas in each state for which soil surveys were published between July 1, 1957, and October 1, 1964. Soil surveys for which field mapping has been completed and soil survey manuscripts submitted for publication are also included. This tabulation supplements the listing published in Highway Research Board Bulletin 22-R, July 1957.

Generally the same type of information is shown about each of the soil surveys listed in this tabulation as was given for those soil surveys listed in Bulletin 22-R. Each published soil survey on this list may be obtained from the Soil Conservation Service, either in the local office or by writing to the Information Division, Soil Conservation Service, U. S. Department of Agriculture, Washington, D. C. 20250.

The soil survey publications which contain interpretations and evaluations of the survey information specifically for engineering purposes are indicated by an asterisk (*) immediately following the name of the survey area. The date shown in the "Year" column is the year in which field survey work was completed. Under "Publication Status" three categories are listed as follows:

In Edit.—Field work completed. Manuscript in SCS Editorial Unit. Publication expected before April 1, 1966.

In GPO—Maps and manuscript in Government Printing Office. Publication expected before October 1, 1965.

Publ.—Soil survey maps and manuscript have been published and are available from the Soil Conservation Service.

Each survey listed has been rated according to the system used in classifying the soils, the scale and type of base maps used in field mapping, and the degree of detail in soil classification and mapping. These ratings are shown in the column headed "Rating." An explanation of each rating is given in Bulletin 22-R.

The Soil Conservation Service has revised, as of April 1, 1964, the national map showing the location and rating of published soil surveys. This is a revised edition of the map showing published soil surveys in Bulletin 22-R. Copies of the revised map have been distributed to all state offices of the Soil Conservation Service or may be obtained by writing to the Soil Conservation Service, U. S. Department of Agriculture, Washington, D. C. 20250.

Paper sponsored by Committee on Exploration and Classification of Earth Materials.

No.	Area Name	Year	Rating	Publication Status	Remarks
			ALABAMA		
2	Baldwin County*	1960	la	In GPO	Replaces 1909 publication
8	Calhoun County*	1958	la	Publ.	Replaces 1908 publication
19	Coosa County	1929	3	Publ.	Replaces 1912 publication
22	Cullman County*	1959	la	Publ.	Replaces 1908 publication
23	Dale County*	1956	la	Publ.	Replaces 1910 publication
25	DeKalb County*	1951	la	Publ.	
29	Fayette County*	1962	la	In Edit.	Replaces 1917 publication
30	Franklin County*	1961	la	In GPO	Replaces 1927 publication
45	Madison County	1947	la	Publ.	
48	Marshall County	1956	la	Publ.	
51	Montgomery County*	1957	la	Publ.	Replaces 1926 publication
52	Morgan County	1944	la	Publ.	
			ALASKA		
1	Alaska Reconnaissance	1914	4	Publ.	
2	Fairbanks Area*	1959	la	Publ.	
3	Kenai-Kasilof Area*	1958	la	Publ.	
4	Kenai Peninsula	1916	3	Publ.	
5	Northeastern Kodiak Island*	1956	la	Publ.	
			ARIZONA		
21	Holbrook-Show Low Area*	1956	la	Publ.	Replaces Navajo County SCD
			ARKANSAS		
6	Bradley County*	1958	la	Publ.	Replaces 1925 publication
			CALIFORNIA		
67	Santa Clara Area	1941	lb	Publ.	Part of Santa Clara County
70	Santa Barbara Area	1944	lb	Publ.	Part of Santa Barbara County
71	Merced Area	1950	la	Publ.	Part of Merced County
72	Madera Area	1951	la	Publ.	Part of Madera County
73	San Mateo Area*	1954	la	Publ.	Part of San Mateo County
74	Eastern Stanislaus*	1957	la	Publ.	Part of Stanislaus County
75	Amador Area*	1961	la	In GPO	Part of Amador County
76	Alameda Area*	1961	la	In Edit.	Part of Alameda County
			COLORADO		
12	Fraser Alpine Area	1956	la	Publ.	Parts Clear Creek, Grand and Summit Counties
13	Trout Creek Watershed*	1958	la	Publ.	Parts Chaffee and Park Counties
			CONNECTICUT		
2	Hartford County*	1958	la	Publ.	
7	Tolland County*	1961	la	In Edit.	

No.	Area Name	Year	Rating	Publication Status	Remarks
			FLORIDA		
13	Dade County	1947	lb	Publ.	
17	Escambia County*	1955	la	Publ.	
20	Gadsden County*	1959	la	Publ.	Replaces 1903 publication
29	Hillsborough County	1950	la	Publ.	
41	Manatee County	1947	la	Publ.	
48	Orange County*	1957	la	Publ.	Replaces 1919 publication
58	Sarasota County*	1954	la	Publ.	
61	Suwannee County*	1961	la	In GPO	
67	Washington County*	1962	la	In GPO	
			GEORGIA		
48	Douglas County*	1959	la	Publ.	
60	Fulton County	1949	la	Publ.	
64	Gordon County*	1962	la	In Edit.	Replaces 1913 publication
68	Habersham County*	1959	la	Publ.	Replaces 1913 publication
73	Hart County*	1961	la	Publ.	Replaces 1929 publication
95	McIntosh County*	1959	la	Publ.	Replaces 1929 publication
99	Meriwether County*	1961	la	In GPO	Replaces 1916 publication
104	Morgan County*	1962	la	In GPO	Replaces 1919 publication
126	Spalding County*	1961	la	Publ.	Replaces 1905 publication
137	Tift County	1946	la	Publ.	
140	Treutlen County*	1961	la	Publ.	
143	Twiggs County*	1960	la	Publ.	
147	Walton County*	1961	la	In GPO	
151	Wayne County*	1961	la	In GPO	
			HAWAII		
1	Territory of Hawaii	1939	2	Publ.	
			IDAHO		
23	Gem County*	1958	la	In GPO	
			INDIANA		
8	Carroll County	1940	lb	Publ.	
21 81	Fayette County Union County	1952	la	Publ.	One publication
60	Owen County	1959	la	In GPO	
72	Scott County	1958	la	Publ.	
79	Tippecanoe County	1940	lb	Publ.	
			ILLINOIS		
93	Wabash County*	1957	la	Publ.	Replaces 1937 publication
100	Williamson County	1955	la	Publ.	By the Experiment Station
			IOWA		
2	Adams County*	1958	la	Publ.	
3	Allamakee County	1939	lb	Publ.	
46	Humboldt County	1956	la	Publ.	
51	Jefferson County*	1954	la	Publ.	

No.	Area Name	Year	Rating	Publication Status	Remarks
		IOWA (Continued)			
59	Lucas County	1956	la	Publ.	
67	Monona County*	1952	la	Publ.	
77	Polk County	1953	la	Publ.	
83	Shelby County*	1956	la	Publ.	
89	Van Buren County*	1958	la	Publ.	
		KANSAS			
7	Brown County	1955	la	Publ.	
28	Finney County*	1961	la	In GPO	
29	Ford County*	1958	la	In GPO	
31	Geary County	1955	la	Publ.	
36	Greeley County	1958	la	Publ.	
38	Hamilton County	1958	la	Publ.	
47	Kearney County*	1959	la	Publ.	
55	Logan County*	1959	la	Publ.	
65	Morton County*	1960	la	Publ.	
78	Reno County*	1962	la	In Edit.	Replaces 1911 publication
85	Saline County	1950	la	Publ.	
86	Scott County*	1961	la	In Edit.	
88	Seward County*	1961	la	In GPO	
94	Stanton County	1958	la	Publ.	
95	Stevens County	1958	la	Publ.	
102	Wichita County*	1962	la	In Edit.	
		KENTUCKY			
1	Adair County*	1961	la	Publ.	
6	Bath County*	1959	la	Publ.	
25	Clark County*	1961	la	In GPO	
32	Elliott County*	1961	la	In GPO	
38	Fulton County*	1961	la	Publ.	
56	Jefferson County*	1962	la	In Edit.	
	Eastern Kentucky Reconnaissance	1962	x	In GPO	Fourteen counties
		LOUISIANA			
1	Acadia Parish*	1959	la	Publ.	
8	Bossier Parish*	1959	la	Publ.	
51	St. Mary Parish	1952	la	Publ.	
55	Terrebonne Parish	1956	la	Publ.	
		MAINE			
10	Penobscot County*	1959	la	Publ.	
3	Aroostook Area*	1958	la	Publ.	Northeast part of county
5	Aroostook Area*	1961	la	Publ.	Southern part of county
		MARYLAND			
5	Caroline County*	1959	la	Publ.	
9	Dorchester County*	1959	la	Publ.	
10	Frederick County*	1956	la	Publ.	
15	Montgomery County*	1958	la	Publ.	
21	Washington County*	1959	la	Publ.	

No.	Area Name	Year	Rating	Publication Status	Remarks
			MICHIGAN		
28	Grand Traverse County	1958	la	In Edit.	
46	Lenawee County	1947	la	Publ.	
59	Montcalm County	1949	lb	Publ.	
76	Sanilac County*	1953	la	Publ.	
			MINNESOTA		
18	Crow Wing County*	1957	la	In GPO	
19	Dakota County	1955	lb	Publ.	
20	Dodge County*	1956	la	Publ.	
22	Faribault County	1947	lb	Publ.	
23	Fillmore County	1954	la	Publ.	
30	Isanti County*	1953	lb	Publ.	
52	Nicollet County	1948	lb	Publ.	
70	Scott County*	1955	lb	Publ.	
79	Wabasha County*	1959	la	In GPO	
81	Waseca County*	1961	la	In GPO	
			MISSISSIPPI		
7	Calhoun County*	1962	la	In GPO	
11	Claiborne County*	1960	la	Publ.	Replaces 1926 publication
12	Clarke County*	1961	la	In GPO	Replaces 1914 publication
14	Coahoma County*	1950	la	Publ.	
16	Covington County*	1961	la	In GPO	Replaces 1917 publication
17	De Soto County*	1953	la	Publ.	
27	Humphreys County*	1954	lb	Publ.	
28	Issaquena County*	1959	la	Publ.	
30	Jackson County*	1960	la	Publ.	Replaces 1927 publication
42	Leflore County*	1957	la	Publ.	
43	Lincoln County*	1960	la	Publ.	Replaces 1912 publication
48	Monroe County*	1961	la	In Edit.	Replaces 1908 publication
51	Newton County*	1957	la	Publ.	Replaces 1916 publication
54	Panola County*	1960	la	Publ.	
60	Quitman County*	1947	lb	Publ.	
63	Sharkey County*	1959	la	Publ.	
67	Sunflower County*	1952	la	Publ.	
70	Tippah County*	1963	la	In Edit.	
75	Warren County*	1961	la	In GPO	
76	Washington County*	1958	la	Publ.	
			MISSOURI		
10	Boone County	1951	la	Publ.	
31	Daviess County*	1959	la	Publ.	
68	Moniteau County*	1953	la	Publ.	
			MONTANA		
23	Judith Basin County*	1959	la	In Edit.	
55	Wibaux County	1943	la	Publ.	
11	Upper Flathead Valley	1946	la	Publ.	
12	Bitterroot Valley Area	1951	lb	Publ.	Replaces 1914 publication

No.	Area Name	Year	Rating	Publication Status	Remarks
			NEBRASKA		
25	Deuel County*	1960	la	In GPO	Replaces 1921 publication
29	Dundy County*	1959	la	Publ.	
34	Gage County*	1959	la	Publ.	Replaces 1914 publication
40	Hall County*	1957	la	Publ.	Replaces 1916 publication
46	Hooker County*	1960	la	Publ.	
53	Kimball County	1957	la	Publ.	Replaces 1916 publication
63	Nance County	1955	la	Publ.	
78	Saunders County*	1959	la	In GPO	
86	Thomas County*	1962	la	In GPO	
89	Washington County*	1957	la	In GPO	Replaces 1915 publication
			NEVADA		
4	Las Vegas Valley and Eldorado Valley	1956	la	In Edit.	Name change
5	Lovelock Area	1958	la	In GPO	
			NEW HAMPSHIRE		
7	Merrimack County*	1961	la	In GPO	
8	Rockingham County*	1954	lb	Publ.	
			NEW JERSEY		
4	Camden County*	1961	la	In Edit.	
8	Gloucester County*	1959	la	Publ.	
			NEW MEXICO		
5	Curry County	1953	la	Publ.	
11	Portales Irrigated Area	1954	la	Publ.	Part of Roosevelt County
12	Bluewater Area	1955	la	Publ.	Part of Valencia County
			NEW YORK		
12	Cortland County*	1957	la	Publ.	Replaces 1916 publication
17	Franklin County*	1952	la	Publ.	
25	Lewis County	1954	la	Publ.	
35 62	Ontario and Yates Counties	1949	la	Publ.	One publication
55	Tompkins County*	1961	la	In GPO	
			NORTH CAROLINA		
1	Alamance County*	1956	la	Publ.	
31	Duplin County*	1954	la	Publ.	
49	Iredell County*	1960	la	Publ.	
70	Pasquotank County	1949	la	Publ.	
95	Watauga County	1944	la	Publ.	
99	Yadkin County*	1959	la	Publ.	
			NORTH DAKOTA		
41	Sargent County*	1958	la	Publ.	

No.	Area Name	Year	Rating	Publication Status	Remarks
			OHIO		
2	Allen County*	1960	1a	In GPO	
12	Clark County	1949	1a	Publ.	
14	Clinton County*	1958	1a	Publ.	
23	Fairfield County*	1951	1a	Publ.	
63	Paulding County*	1954	1a	Publ.	
87	Wood County*	1958	1a	In Edit.	
			OKLAHOMA		
1	Adair County*	1961	1a	In GPO	
4	Beaver County*	1959	1a	Publ.	
13	Cimarron County*	1956	1a	Publ.	
17	Cotton County*	1960	1a	Publ.	
19	Creek County	1950	1a	Publ.	
22	Dewey County*	1960	1a	Publ.	
23	Ellis County*	1961	1a	In Edit.	
30	Harper County*	1956	1a	Publ.	
33	Jackson County*	1958	1a	Publ.	
37	Kingfisher County*	1959	1a	Publ.	
42	Logan County*	1948	1a	Publ.	
58	Ottawa County*	1960	1a	In GPO	
59	Pawnee County*	1952	1a	Publ.	
65	Roger Mills County*	1959	1a	Publ.	
66	Rogers County*	1961	1a	In Edit.	
69	Stephens County*	1960	1a	In GPO	
70	Texas County*	1958	1a	Publ.	Replaces 1930 publication
77	Woodward County*	1960	1a	Publ.	Replaces 1932 publication
			OREGON		
28	Sherman County*	1959	1a	In GPO	
11	Deschutes Area	1945	1a	Publ.	
12	Prineville Area	1955	1a	In Edit.	
13	Tillamook Area*	1957	1a	Publ.	
			PENNSYLVANIA		
13	Carbon County*	1959	1a	Publ.	
15	Chester County*	1959	1a	Publ.	Replaces 1905 publication
16	Clarion County*	1955	1a	Publ.	
18	Clinton County*	1961	1a	In Edit.	
23	Delaware County*	1959	1a	Publ.	Chester and Delaware are one publication
25	Erie County*	1957	1a	Publ.	Replaces 1910 publication
33	Jefferson County*	1960	1a	In GPO	
36	Lancaster County*	1956	1a	Publ.	
39	Lehigh County*	1959	1a	Publ.	
53	Potter County*	1953	1b	Publ.	
67	York County*	1959	1a	Publ.	Replaces 1912 publication
			RHODE ISLAND		
1&3	Bristol & Newport Co's	1936	2	Publ.	Error in classification in Bulletin 22-R
2&5	Kent & Washington Co's	1934	2	Publ.	
4	Providence County	1938	2	Publ.	

No.	Area Name	Year	Rating	Publication Status	Remarks
			SOUTH CAROLINA		
5	Bamberg County*	1962	la	In Edit.	Replaces 1913 publication
9	Calhoun County*	1961	la	Publ.	
11	Cherokee County*	1958	la	Publ.	Replaces 1905 publication
16	Darlington County*	1957	la	Publ.	
31	Lee County*	1959	la	Publ.	Replaces 1907 publication
35	Marlboro County*	1962	la	In GPO	Replaces 1917 publication
36	Newberry County	1956	la	Publ.	Replaces 1918 publication
37	Oconee County*	1958	la	Publ.	
41	Saluda County*	1958	la	Publ.	Replaces 1909 publication
46	York County*	1961	la	In GPO	Replaces 1905 publication
			SOUTH DAKOTA		
6	Brookings County*	1955	la	Publ.	
30	Hand County*	1956	la	Publ.	
50	Minnehaha County*	1958	la	Publ.	
			TENNESSEE		
5	Blount County*	1953	la	Publ.	
6	Bradley County	1951	la	Publ.	
16	Coffee County*	1956	la	Publ.	
23	Dyer County*	1962	la	In Edit.	
24	Fayette County*	1960	la	Publ.	
26	Franklin County	1949	la	Publ.	
30	Greene County	1947	la	Publ.	
36	Hardin County*	1960	la	Publ.	Replaces 1926 publication
39	Henderson County*	1954	la	Publ.	
40	Henry County	1948	lb	Publ.	
42	Houston County	1949	la	Publ.	
50	Lawrence County	1952	la	Publ.	
53	Loudon County*	1958	la	Publ.	
54	McMinn County	1948	lb	Publ.	
58	Marion County	1950	la	Publ.	
60	Maury County*	1952	la	Publ.	
71	Putnam County*	1960	la	Publ.	Replaces 1912 publication
90	Washington County	1948	la	Publ.	
94	Williamson County*	1961	la	Publ.	
			TEXAS		
6	Armstrong County*	1961	la	In GPO	
9	Bailey County*	1959	la	Publ.	
15	Bexar County*	1962	la	In Edit.	
21	Brazos County*	1951	la	Publ.	
33	Carson County*	1959	la	Publ.	
37	Cherokee County	1948	lb	Publ.	
38	Childress County*	1960	la	Publ.	
40	Cochran County*	1960	la	Publ.	
54	Crosby County*	1961	la	In Edit.	
58	Dawson County*	1957	la	Publ.	
70	Ellis County*	1961	la	Publ.	
76	Fisher County*	1961	la	In Edit.	
78	Foard County*	1961	la	In GPO	
79	Fort Bend County*	1955	la	Publ.	
83	Gaines County*	1961	la	In Edit.	

No.	Area Name	Year	Rating	Publication Status	Remarks
			TEXAS (Continued)		
98	Hansford County*	1957	la	Publ.	
104	Haskell County*	1958	la	Publ.	
110	Hockley County*	1961	la	In GPO	
123	Jefferson County*	1960	la	In GPO	
140	Lamb County*	1959	la	Publ.	
153	Lynn County	1953	la	Publ.	
155	McLennan County	1942	lb	Publ.	
178	Nueces County*	1960	la	In GPO	
223	Terry County*	1959	la	Publ.	
244	Wilbarger County*	1959	la	Publ.	
251	Yoakum County*	1960	la	Publ.	
			UTAH		
12	Roosevelt-Duchesne A.	1940	lb	Publ.	Part of Duchesne County
13	East Millard Area	1944	la	Publ.	Part of Millard County
14	Richfield Area	1944	lb	Publ.	Part of Sevier County
15	San Juan Area	1945	lb	Publ.	Part of San Juan County
16	Central Utah County			In Edit.	Change of name
17	Beryle-Enterprise Area	1952	lb	Publ.	Part of Iron County
18	Davis-Weber Area			In Edit.	Parts of both Counties
			VERMONT		
7	Grand Isle County	1953	la	Publ.	
			VIRGINIA		
30	Fairfax County*	1955	la	Publ.	
33	Fluvanna County	1947	la	Publ.	
52	Lancaster County*	1959	la	Publ.	Northumberland and Lancaster Counties in one publication
54	Loudoun County	1951	la	Publ.	
58	Mathews County*	1958	la	Publ.	
65	Norfolk County*	1953	la	Publ.	
67	Northumberland County*	1959	la	Publ.	See Lancaster County
68	Nottoway County*	1954	la	Publ.	
74	Prince Edward County	1949	la	Publ.	
79	Rappahannock County*	1958	la	Publ.	
			WASHINGTON		
15	Island County	1949	lb	Publ.	
23	Mason County	1951	lb	Publ.	
28	San Juan County*	1957	la	Publ.	
29	Skagit County	1951	la	Publ.	
34	Thurston County	1947	lb	Publ.	
36	Walla Walla County*	1957	la	Publ.	
39	Yakima County	1942	lb	Publ.	

No.	Area Name	Year	Rating	Publication Status	Remarks
			WEST VIRGINIA		
2	Berkeley County*	1958	la	In Edit.	Replaces Berkeley County part of 1916 publication
18	Jackson County*	1957	la	Publ.	
26	Marshall County*	1957	la	Publ.	
27	Mason County*	1957	la	Publ.	
32	Monroe County*	1960	la	In GPO	
39	Preston County*	1954	la	Publ.	
			WISCONSIN		
3	Barron County	1948	la	Publ.	
4	Bayfield County*	1939	lb	Publ.	
6	Buffalo County*	1957	la	Publ.	
12	Crawford County*	1958	la	Publ.	
22	Grant County*	1951	la	Publ.	
25	Iowa County*	1958	la	Publ.	
32	LaCrosse County*	1956	la	Publ.	
33	Lafayette County*	1960	la	In Edit.	
46	Pepin County*	1958	la	Publ.	
52	Richland County	1949	la	Publ.	

Statistically Controlled Engineering Soil Survey

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ABRIDGMENT

•ONE OF THE most common practices of roadway soil survey specifies that soil borings should be made at regular intervals along the alignment of the proposed transportation route. However, this approach is not satisfactory since it fails to take into consideration the distribution and the variability in the properties of various types of surficial soils encountered throughout the proposed alignment. A method for distributing the soil borings on the basis of the variability of individual soil types and their distribution along a proposed alignment is thus proposed.

The proposed method is illustrated for an hypothetical highway alignment approximately 3.4 miles long in Will County, Ill., which has an up-to-date pedological soil survey map. In connection with the Illinois Cooperative Highway Research Program, an extensive soil investigation program was conducted by testing samples from five or more sites of each pedological soil type encountered in the county. For each soil type, the mean, standard deviation, and coefficient of variation (which expresses the standard

TABLE 1

Soil Type No.	Total Length in 100 Ft	No. of Borings		
		On Basis of Max. Coef. of Var.	On Basis of Avg. Coef. of Var.	At 150-Ft Interval
59	6.5	5	5	4
67	16.5	14	13	11
145	20.5	10	13	14
146	43.5	18	18	29
152	27.5	32	32	19
232	33.0	19	15	23
293	4.5	4	4	2
294	8.0	2	3	5
318	6.0	8	9	4
325	5.5	3	3	4
326	7.0	4	4	4
Total	178.5	119	119	119

Paper sponsored by Committee on Exploration and Classification of Earth Materials and and presented at the 44th Annual Meeting.

deviation as a percentage of the mean) values of the liquid limit, plasticity index, percent fines (<0.074 mm), and percent clay (<0.002 mm) were calculated. Both the maximum and average coefficient of variation values for the four index properties of the C-horizon of each soil type are used as statistical control factors. In this way, the relative variability of various soil types encountered by the hypothetical alignment are taken into account. The product of the length of each soil type area measured along the alignment and its maximum or average coefficient of variation value is defined as the sampling factor.

The total number of borings to be made within a section of the alignment for the Federal-Aid Interstate System is determined by assuming that borings will be required on the average for the two divided lanes at an interval of one every 150 ft. It is also planned that at least one boring must be made in each soil-type area. The rest of the borings are proportioned in each soil-type area according to the ratio of its individual sampling factor to the sum of the sampling factors for the entire section. The results of the two distribution procedures are summarized in Table 1.

The following observations can be made from Table 1:

1. The number of borings distributed in each soil type is approximately the same whether the maximum or the average coefficient of variation value was used as the statistical control factor because either of these two coefficients expresses the same relative variability among the soil types.

2. The number of borings required on the basis of sampling at regular intervals is nearly doubled for Soil Types 152, 293, and 318 in the case where the borings are distributed on a statistical basis. Conversely, for Soil Types 146, 232, and 294, the number of borings is nearly halved. The test data clearly show that the physical properties of the first group of soil types are more variable than those of the second group.

Because this boring program takes advantage of knowledge of the variability of any given natural soil unit, it will avoid the following problems resulting from a regular pattern of soil borings:

1. The possibility of missing a detrimental soil type which may cause problems out of proportion to the size of area it occupies;

2. The chance of placing a very small number of borings in an extremely erratic soil type which may be responsible for the major engineering problems along the proposed alignment; and

3. The sampling of a uniform soil type many more times than necessary to determine its average characteristics and variability.

The complete manuscript is published as University of Illinois, Civil Engineering Studies, Soil Mechanics Series No. 9. Copies of that publication can be obtained from the authors.