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

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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

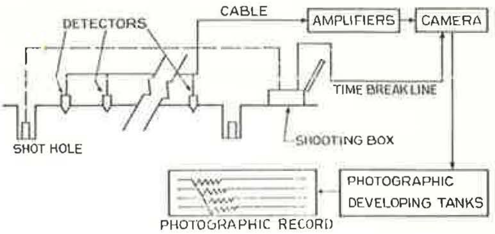

Figure 1. Complete seismograph system.

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 1/2 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.

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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):

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

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

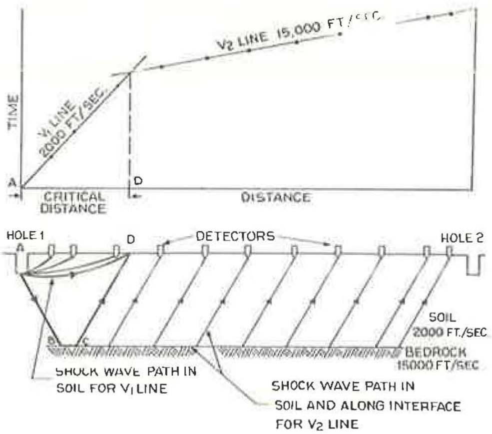

Figure 2. Seismograph time-distance graph and geologic profile.

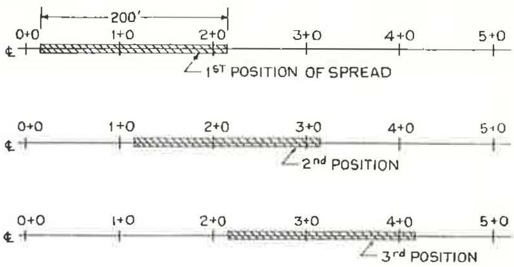

Figure 3. Successive positions of a 200-ft spread used in the continuous profile method.

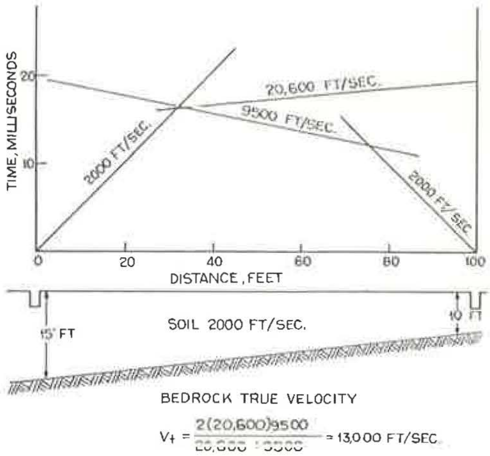

Figure 4. Time-distance graph for an inclined interface.

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):

$$V_t = \frac{2\ V_u\ V_d}{V_u + V_d} \tag{2}$$

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.

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

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:

$$D' = h + h' \tag{4}$$

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.