SEISMOLOGY AS A GEOLOGIC TECHNIQUE

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This paper, as one of three treating geological and seismological research and their application to highway location and design, deals especially with the seismological aspect of the study. The seismic surveys were operated by Weston Observatory, a department of Boston College, Chestnut Hill, Massachusetts.

For a more complete understanding of the seismic refraction method as used in these surveys, the reader is referred to the texts listed at the end of this paper. However, in consideration for these unfamiliar with the method and who may not have the time or opportunity to study a text, a very brief outline of the procedure is inserted.

The Method The seismic method is based primarily on the measurement of the time for the advance of a wave front generated from an explosion. This measurement is made by timing the arrival of the wave at various instruments placed in progression away from the explosion or "shot point".

The diagram, Figure 4, represents the advance of a wave front in a two layer structure consisting of about 80 ft. of gravel on bedrock. The wave travels about 5,000 ft. per sec. in the gravel, and about 20,000 ft. per sec. in the bedrock. In such a condition a wave front will be an approximate sphere of 50-ft. radius .01 sec. after it leaves the shot point as represented in the diagram. About .016 sec. after the shot, it reaches the rock surface at point A. From this point of contact a wavelet starts into the rock with a velocity of 20,000 ft. per sec. and .02 sec. after the shot the wavelet has reached the distance noted by that circle in the diagram, not only vertically below A, but radiating in all directions within the rock, so that even along the gravel-rock contact the wave front has reached the point B. However, along the contact the the wave in the rock starts a new series of wavelets that emanate into the gravel and are directed to the gravel surface. The wavelets at B and C are but two of many such wavelets present, and their envelope is the new refracted wave as shown (D-E) .025 sec. after the shot.

Figure 5 diagrams the continued advance of the wave front until .05 sec. after the shot, with the arrival times at the instruments plotted against the distance from the shot point. Clearly, the wave front through the gravel travels on to each instrument at 5,000 ft. per sec., but there is a point along the line, or profile, where the wave front refracted from the rock, owing to its higher velocity gained from the rock, will reach an instrument before the direct wave. In the diagram this is a point a little more than 200 ft. from the shot point. Thus the velocities of the materials may be determined; those of the earlier arrivals may be computed to be 5,000 ft. per sec., the velocity of the gravel in the problem, and the later arrivals fall along a line whose slope equals 20,000 ft. per sec., or the velocity of the bedrock. The distance from the shot point to the point of intersection of these two lines is controlled by the thickness of the

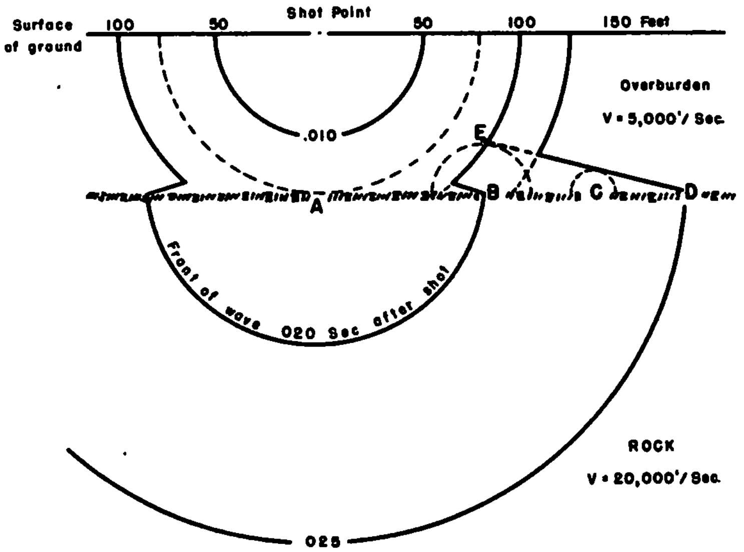

Figure 4. Diagram To Illustrate Successive Positions Of An Advancing Wave Front Generated From An Explosion, In A Two-Layer Region

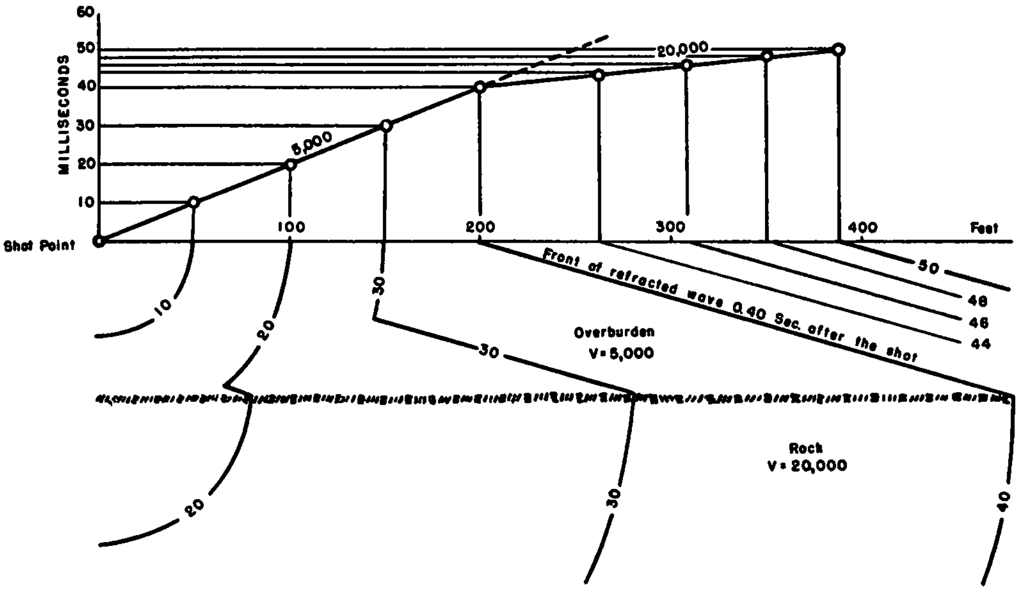

Figure 5. Diagram Of Wave Fronts, And The Related Travel-Time Graph For A 400-Foot Refraction Profile, In A Two-Layer Region

gravel, and the greater the thickness, the greater will be the distance of the intersection from the shot point. From this the seismologist is able to determine the depth to bedrock. The velocities are functions of the types of soil cover and bedrock. A few of these velocities will be listed below.

Furthermore, and as may readily be seen, if the rock surface is inclined instead of parallel to the surface of the ground, the velocities of the rock as determined will differ according to the direction in which the shot was recorded. Such velocities are known as the "apparent" velocities. If the rock surface slopes downward from the shot point, the refracted wave will have to travel farther to the surface at each successive instrument and the velocity will be slower than the "true" velocity of the rock. If the rock slopes upward from the shot point there is less distance for the wave to travel and the apparent velocity is greater than the true one. The true velocity value must be computed from the two apparent velocities; these do indicate, however, the direction and approximate amount of slope of a rock surface. Hence, each profile must be "reversed," that is, shot points are taken at both ends of the instrumental set-up or profile.

Again, if the rock surface is smooth the arrival times will fall along a straight line; if the surface is irregular the arrival times will vary according to the rise or fall of the rock surface. The positions of these points generally give a mirror reflection of the rock surface.

Field Equipment Employed The seismic equipment employed in making these surveys is owned in part by Weston Observatory, and in part is on loan to the Observatory by the Humble Oil and Refining Company, Houston, Texas. The equipment consists of 12 seismometers of the magnetic-reluctance type suitable for surface or underwater work, 12 amplifiers, recording camera, darkroom, water supply, two reels holding 750 ft. each of 12-channel cable, ground augers, etc. These are mounted in a 1½-ton panel truck fitted with four wheel drive and front end winch. Thus the equipment could be carried to almost any type of terrain.

Profile Lengths Outlets on the cable were placed every 100 ft. permitting profiles up to 1100 ft. long to be made with instrument intervals of 100 ft. When closer spacing is desired the extra wire is coiled near the instruments. The closer the spacing used the more detailed will be the bedrock velocity line, although less depth can be determined per set-up and less territory covered per day. The various profile lengths and corresponding depths that may be determined are given below:

Spacing ft.	Profile Length ft.	Depth Desired ft.
10	110	0 to 30
15	165	0 to 40
20	220	10 to 70
50	550	25 to 160
100	1100	50 to 300

Other set-ups have been tried but the above distances are those most commonly used in the types of problems described herein. Such arrangements considered in the light of the method given above will show that the seismologist, geologist, and engineer working together may determine a fairly accurate picture of subsurface conditions. A few of our type problems and results follow.

Bedrock Depth Determinations Depth to bedrock is frequently one of the more important quests of the highway engineer, and fortunately one of the easiest problems for the seismologist to solve. The latter requires but a rock with sufficiently high velocity in comparison with the overburden. In Massachusetts both crystalline and noncrystalline bedrocks transmit longitudinal waves with velocities favorably high. Rarely are the rock velocity constants less than 12,000 ft. per sec., and from what has been explained in the previous paragraphs such velocities facilitate depth determination. Moreover, irregularities in the rock surface as slopes, terraces, etc., stand out clearly with offsets in the velocity line. In some of the metamorphosed rocks of Massachusetts, local parts of the rock may raise the velocity under an instrument or two; such an effect might be misleading and usually calls for several cross profiles as well as the reversal to delineate the bedrock surface. The opinion of the geologist and his knowledge of the local geology plays a great part in the interpretation of such conditions.

Determination of Soils, Gravels, Etc. Sound velocities are frequently indicative of the type of cover, and the following table is characteristic of some of these deposits in Massachusetts.

Evidently, the overlapping of these velocities precludes any exact designation of many of the buried deposits, but the velocity range does give some measure of the engineering characteristics of the material, especially its strength, that are determined by compactness and crystallinity.

Throughout the greater part of Massachusetts it is quite impossible to determine the depth of the water table by the seismic method because most of the materials, wet or dry, have velocities in that range. On Cape Cod, where the unconsolidated surface sediments may extend to depths of several hundred feet, we believe we have located water tables in places but to date we have not been able to check our data against borings. These velocities may change during the season of the year depending upon the water content of the soils, that is, the marked rise and fall of the water table.

Velocity ft. per sec.	Material
1,000 to 2,000	Dry loam; some aeolian deposits.
1,500 to 3,000	Dry sands; loose till, etc.
3,500 to 5,500	Compact tills; gravels within the water table, etc. Some clays.
5,000	Varved clays in Connecticut River Valley.
6,000 to 8,500	"Hardpan" compact older tills, etc; some foliated bedrock across schistocity

Road Cuts Through Clays If a clay layer is thin it may not be detected unless the instrumental spacing is very short; with greater thickness its detection is possible by seismic methods, and such detection is necessary if a road cut passes into or through the clay. If such a layer appears on the face of the cut, it may drain water from the surrounding area onto the cut face and cause erosion. It is also important to know whether this layer is draining into the cut or away from it.

In Chicopee such a site was surveyed seismically with very good results. The varved clays present gave velocities of exactly 5,000 ft. per sec., and the sand cover was less than 2,000 ft. per sec. Instruments were spaced at 5-ft. intervals and the sound energy was supplied in some cases by striking the ground with a shovel. Small depressions, dips, etc., were easily seen in the surface of these clays.

Bridge Foundations Although bedrock might be desired for a bridge foundation, it is not always necessary. If it is too deep, then a compact till is satisfactory and the shape and structure of the foundation is determined by the supporting strength of the material. Borings alone may be misleading in glaciated regions owing to the presence of boulders or variations in the surface of the till.

At Shelburne Falls, a site treated more completely in another paper of this series, the seismic data demonstrated bedrock some distance below the refusal depths of the borings (see Figure 2). As is evident from the profile of this section, the borings stopped at the till surface. However, the seismic data did show an area of low velocity cutting into the till surface across two parallel profiles. This was interpreted as an early drainage channel that became filled with lower velocity material, and, for the engineer, material of less strength. Without the accompanying seismic data the results of the driller might prove confusing here.

Location of Fill Materials having good binding properties for fill in dams, retaining walls, etc., are easily discovered from their velocities. Deposits with velocities from 6,000 to 8,000 ft. per sec. appear to satisfy the engineer's requirements. Frequently these materials are buried under other deposits and unless the seismic method is employed in searching for them, the investigation may become expensive. One example of such a deposit was surveyed in Worcester. The seismic data showed a cover of about 20 ft. of low velocity material over 70 ft. of high velocity till. The entire area was surveyed seismically and the approximate number of cubic yards of material could be determined. Borings at one point brought up samples that met the engineers' demands.

Close Spacing of Instruments Close spacing of instruments, as mentioned above, affords detail on bedrock and cover conditions. At times, however, a plethora of detail may confuse the interpreter, a case of not seeing the woods because too many trees obscure the line of vision. Where the rock surface is very irregular the variations of the velocity lines are likewise so irregular that the determination of a true velocity may be almost impossible. The apparent velocities run the gamut from extremely low to very high and even "negative" velocities. Under these conditions it is better to operate several wider-spaced profiles merely to obtain the true velocity and a general idea of the bedrock slope. Afterwards the shorter profiles become understandable and cross profiling clarifies the picture.

In Peabody a pass under U.S. Route No. 1 requiring at least 20 ft. of cut demonstrates the use of this spacing. The plan of this area with ledge and apparent ledge outcrops made the proposal appear expensive. This plan as given in Figure 3 shows the locations of bedrock outcrops and of the operated profiles.

A seismic survey was run along the centerline using 110 ft. profiles, with one 220 ft. profile from A to C to determine bedrock velocities where conditions were least confusing. Cross profiles were

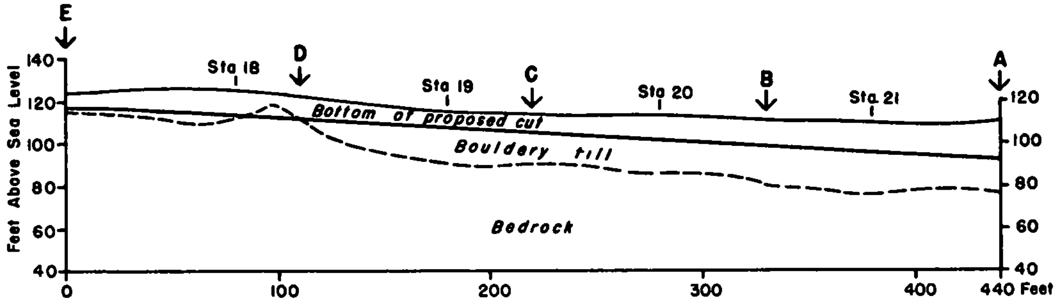

Figure 6. Geologic Interpretation of Seismic Profiles Along Centerline Underpass of Route U. S. 1, Peabody, Massachusetts (see also Figure 3).

also freely used to check the centerline profiles as well as the depth along the width of the cut. Evidence of a sharp rise between stations 17 and 18 resulted from the seismic survey, and after several cross and angular profiles in this vicinity the seismologist interpreted this rise to be in the shape of a small but prominent knob. These profiles also showed some apparent outcrops to be large boulders. Near G is a large outcrop ledge, but the seismic evidence showed that this ledge dropped abruptly, so that a few feet away from it bedrock was at least 20 ft. deep. Excavation to date has broadly substantiated the seismic interpretation. The ledge has been found to drop sharply, and certain apparent outcrops are very large boulders, one of which is at least 10 ft. in diameter. The knob of rock rises, but is approximately 20 ft. to the west of the spot indicated and a little off the centerline. The seismic profile of this traverse appears in Figure 6, a heavy line showing the exact position of the ledge as uncovered and a dotted line showing the amount of excavation to date of this paper.

Difficulties Several times during the excavation at the Peabody site, just described, the steam shovel operator was under the impression that ledge had been reached above the seismic line, but further excavation proved such to be boulders. We have found it difficult to distinguish between so-called "boulder nests" and rock surface irregularities. Usually, when such discrepancies appear, our profile line signifies velocity changes that might indicate either. Financially it will prove as expensive to excavate large boulders as it does ledge, although planning by the engineer for drainage, etc., may not be as complicated. It is unfortunate that a greater distinction in these velocity lines was not obtainable. It will be several months before the cut is completed at this site, and, no doubt, further excavation will delineate conditions different in some respect from the simple interpretation of the seismologist. We feel that the general picture will not differ too much from it and experience gained here may be applied to future and similar problems. We have found that the close spacing of short profiles can be worked with success.

Frequent difficulties arise in generating sufficient energy in certain materials. This is true where the ground has been reworked, and material such as quarried stone has been dumped as a shallow cover. The lack of binding material in the interstices of the rock pieces damps the sound wave. In some dry sands, ashes, etc., it is better, if possible to place the shot hole outside of or below these materials; they do not permit the generation of a wave, but will readily transmit it once it has been generated outside of the material.

In some swamplands we have met with little success if there is a layer of thick peat on the surface. Our results have not checked with the borings in two such places; at Lunenberg and Manchester. In both places, the record characteristics were such that the seismologist was aware even before plotting that results would not be satisfactory. We are quite certain that our error was due to improper planting of the instruments. Plans have been made to reshoot these swamplands using deeper instrument planting to get below the loose peat on top. When the instruments were placed at the edge of some road fill and out of peat at Lunenberg, the seismic results checked with those of the driller.

In densely populated areas seismic surveying may become difficult, but not impossible. Foot or vehicular traffic may cause sufficient ground unrest to render trimming of the amplifiers so low that the amount of explosive required becomes embarrassing, if not dangerous. Usually, however, it is possible to halt traffic for the few moments of actual shooting operations. Ground unrest from factory operations is another question, and we have to operate during their inactive periods. One factory owner did accomodate us by shutting down his plant while we shot.

Power lines and airports cause trouble at times. The former may be taken care of by proper filtering in the circuits, but the latter not so easily. The airwave from the propeller noise is very troublesome and the larger planes give us the more trouble as the frequency is nearer to that of the instruments.

The proximity of buried water and gas mains, oil tanks, etc., must also be determined beforehand lest an explosive charge be fired too close to them.

Areas of irregular topography may be corrected afterwards in the plotting, but we prefer to operate a profile along a contour line if possible to avoid the later corrections.

Amount and Kind of Explosive Used The amount of explosive used per shot is not great. Profiles of 110 to 220 ft. in length demand no more than ¼ to ½ lb. charge of 60 percent nitro-glycerine. If the shot hole is made with a bar and hammer to a depth of four feet, it will not blow out unless the soil is unusually soft or is wet clay over rock. For longer profiles up to 550 ft. in length, 1 to 2 lbs. of *Nitramon* is used. For these latter charges shot holes are dug with augers to a depth of about six feet. In populated areas or when near power lines, we have made it a general practice to cover all shots with a blasting mat.

Area Covered Per Diem In seismic surveying for highway design and location the amount of work accomplished should be considered in the number of profiles operated rather than the area covered. In open and accessible country, two seismologists, a geologist, an engineer, and four laborers can easily operate eight 110-220 ft. profiles and their reversals in a day. This includes driving the shot holes, tying-in the location, mapping profile elevations, and making preliminary field readings of the records. Where paths must be cut through brush and undergrowth, and the cables "snaked" through obstacles, the number of profiles is decreased. Time could be saved if the cables were standardized to a definite length profile, and the cables thus used for measuring positions as well as profile lengths, but it has proven impossible to choose any standard, as conditions may vary at each location. Whenever possible, the seismologist attempts to make a complete plot of his readings for the day's work. This permits a more judicious placing of profiles on the day following so that other profiles may cover areas of doubtful subsurface conditions. Even then, we have found that, with the seismic work apparently completed for an area, conference with the geologist and engineer has resulted in placing other profiles to clarify the picture.

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DISCUSSION

Philip Keene, *Soils and Foundations Engineer, Connecticut Highway Department* The author is to be congratulated on an interesting paper, forming part of a well-integrated group of three on the use of geological methods in solving some highway problems.

The paper brings two questions to mind regarding information from seismic surveying. These are:

First, is it not often difficult to distinguish between dense glacial till and bedrock? Many glacial tills in Connecticut are composed of exceedingly well-graded soil - boulders, cobbles, gravel, sand, and silt, with or without clay. These silty and clayey tills have densities of 135 to 145 lb. per cu. ft., dry weight, and sometimes must be blasted to be readily excavated. They are definitely soils, for they slough and become "soupy" when subject to unfavorable ground water and surface water conditions. When washed and sieved in the laboratory their component parts are immediately recognized. Their velocity constant might be as high as 10,000 ft. per sec., which is about the same as for weathered rock.

Frequently these tills lie directly on bedrock. One of our foremost seismologists, who is also a leader in the field of seismic surveying, related to me a few years ago his unfortunate experience in a northeastern state where his seismic survey data led him to label as soft bedrock a thick stratum of clayey till which overlay bedrock.

The second question is whether location of rock surface by the seismic method is more accurate in the valleys than on the hills. In Connecticut, rock surface in valleys is frequently irregular, but on the hills it is very much more so.

Closure, Rev. Linehan

The existence of high velocity tills does offer difficulty to the seismologist, but where the bedrock is moderately "hard" interpretation is usually possible and moreover accurate. We have encountered these tills with velocities varying between 6,000 and 10,000 ft. per sec. in Massachusetts, Connecticut, and New York. Subsequent borings have shown these materials to be similar to those described by Mr. Keene.

Rarely, if ever, have we found local bedrock velocities as low as these till velocities, although there might be a difference of only a few thousand feet per second. The solution lies in the arrangement of the profiles. If a system of continuous profiling is operated the till velocities are readily distinguished from those of the bedrock. If, on the other hand, isolated profiles are employed, the computer is apt to confuse the lower till velocity as an apparent low velocity of the bedrock signifying a slope-dip of the bedrock surface. With continuous profiling the computer observes "tie-ins" of till velocities from one profile to another as well as the "tie-ins" of the rock velocities.

Usually the surface of the till is uniform whereas the bedrock surface may be irregular, and this irregularity may be used as an occasional norm in distinguishing between the two materials.

The problem of distinguishing between soft rocks and high velocity tills is a more difficult one to solve. Some Berkshire limestones, for example, are so weathered that they may easily be crumbled by hand, and may offer velocities in the till range. We have operated sections in this area and are awaiting boring data to prove or disprove our interpretation. We believe the velocity of 7500 ft. per sec. encountered there to demonstrate till and not the weathered rock. Again, near Portsmouth, Rhode Island, velocities in shale are so low as to hazard differentiation between these and tills of high velocity. For the geologist, this would offer difficulty in mapping, but it does not present as great a practical difficulty to the engineer. These Portsmouth shales may be excavated as easily by power shovels as the tills, with little or no blasting required. In brief, while the seismologist may not be able to name the material, the velocities will inform him what strength, density, elasticity, and other similar properties the material possesses.

In response to the second question, the accuracy of rock location does depend upon the regularity of the rock surface. The igneous intrusives and metamorphics of New England differ little on account of their location; however, the igneous intrusives and sedimentary series of the Connecticut River Valley may differ greatly. The seismologist can usually tell from his completed graphs what accuracy may be expected.