THE SEISMIC METHOD IN SUBSURFACE EXPLORATION OF HIGHWAY AND FOUNDATION SITES IN MASSACHUSETTS

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In 1938 the Massachusetts Department of Public Works entered into a cooperative agreement with the U.S. Geological Survey to prepare an up-to-date geologic atlas of the Commonwealth by quadrangles on a scale of 2 inches equal 1 mile. The maps were designed to show not only the distribution and nature of the bedrock formations but a set was also to be prepared to show the distribution, materials, and forms of the loose surficial, the engineering soil, materials and the exposures of bedrock ledges. In part of this program geologic information was provided that related to highway and other engineering projects.

First, let us understand what geology is and then what it can furnish in the way of data related to engineering projects. Geology is the science of the earth—its materials, its structure, and its history. It embraces a study of the natural materials that make up the terrain, both at and below the surface, and the forms and structures of these materials. Inasmuch as engineers and contractors work with geologic materials, it follows that a knowledge of their nature, behavior and structure is of practical value. This knowledge can be obtained through geologic field techniques.

Obviously only those materials that are exposed to view may be studied by direct observation. Those that are covered may be interpreted only from data obtained by indirect methods, that is, by inferences based on general knowledge of the geology of the region, or by some means of subsurface exploration. Let it be understood that a geologist does not have X-ray eyes, a crystal ball, or extra-sensory perception. He draws upon his basic geologic knowledge and his

knowledge of the local and regional geology to interpret the probable or possible subsurface conditions at a given site. That, of course, lies within· his particular field of scientific competence. The degree of his success depends upon his background of training and experience. But it is truly and strictly indirect and interpretative. In many instances he can give a shrewd guess—what we might call an educated guess—as to what lies below the surface of the ground. These interpretations, or trained guesses, are, of course, in no sense quantitative, though a geologist may often reasonably suggest that a bedrock ledge is either close to the surface or relatively deep.

For engineering purposes there is needed some way of measuring with a reasonable and practical degree of accuracy, such things as the thicknesses of various soil materials, the depths to bedrock, and the variations in depth of the bedrock surface along the line of excavation. How can this accuracy be attained?

There are three principal methods of approach to quantitative depth data, no one of which is infallible. These are: (1) wash borings, (2) core drillings, and (3) physical tests—or what are called geophysical methods. Borings and core drillings give positive results up to a certain point. They are direct, but they are very limited, as you well know. Geophysical methods are indirect— they do not directly identify materials. Rather they provide data based on certain physical properties of the subsurface materials, and these data must be interpreted in terms of materials known to exist in the region.

Now let us consider the advantages and the limitations of these three ways of solving the

problem of what lies below the surface, at what depths, and in what forms.

First, let us consider wash borings. These are very helpful in many places. They are also very much limited as to what they indicate, particularly with respect to depths to bedrock in a glaciated region like New England where most of the soil materials are not derived in place from the underlying bedrock and the thickness of the soil cover may vary considerably within a few feet. Wash borings give information only at a single point. With them, when you reach refusal, you do not know whether or not it is due to ledge, to a boulder, or to a detached block of bedrock. You may make several wash borings within a few feet and interpret the refusal as a boulder, but it may be a pinnacle or steep-sided knob of bedrock, such as is indicated in figure 1.

The sludges from wash borings, if properly taken and studied, will, of course, commonly disclose the general nature of the soil material, but the structure and grain relationships are totally destroyed; moreover, the sludges are mixed, so that to identify different soil layers accurately requires additional and most careful sampling. Drive sample borings will, of course, provide relatively undisturbed soil samples and permit a more accurate identification of materials, textures, and structures; these, too, increase costs and time. Such soil studies, too, are significant to all of us only if we use a common classification and terminology. A geologist might identify material as glacial till or "hardpan," which commonly contains boulders, and so give a shrewd guess as to whether or not the refusal is a boulder. By the same token, to make several borings in order to identify a refusal increases costs and time. It may be argued that a single core drilling will serve to identify a refusal in this case. This is true if the drill hole goes deeply enough into the

rock, but even then it does not measure the size of the boulder—it gives but one dimension. In New England we have boulders and blocks of rock in excess of 25 feet through; certainly a conventionally limited penetration of 5 or even 10 feet is not sufficient to prove "ledge" rock. Some surface boulders are so large that they have been given contours on the topographic maps!

Core drillings are more satisfactory than wash borings for identifying rock materials but are much more expensive and time consuming. To be adequate in the majority of cases they must penetrate in excess of 10 feet, and as I have indicated, require much deeper penetration for absolute identification. Like wash borings they give information at a single point only. To truly prove up a terrain by enough closely spaced core drillings is prohibitive in time and money, except in some instances, such as sites for heavy bridge piers, where very accurate subsurface data over a small area are needed almost regardless of cost. However, core drillings should be used more than they are in conjunction with other methods of subsurface exploration.

We come now to a discussion of geophysical methods. Two methods are used at engineering sites; these are refraction seismic testing and electrical resistivity. We have used both in highway exploration work in Massachusetts and have found the seismic method to be, by far, the most satisfactory. The seismic method, like other geophysical methods, is indirect insofar as identifying materials is concerned. The results are, therefore, interpreted from local and regional geologic data into materials known to exist in the specific area. The results are quantitative to some degree, but by no means do they approach a slide rule or engineering accuracy. Sometimes they depart very widely from desired or practical accuracy. The degree of accuracy depends upon such things as homogeneity and uniformity of the materials, and the simplicity of their structures, surfaces, and interfaces. Nowhere do these ideal conditions exist, so that interpretation of seismic results depends all the more on the geologist's terrain knowledge and experience.

Let us now examine the refraction seismic test procedure. The test measures the speed of certain elastic waves or impulses sent through the materials. The speed (sometimes
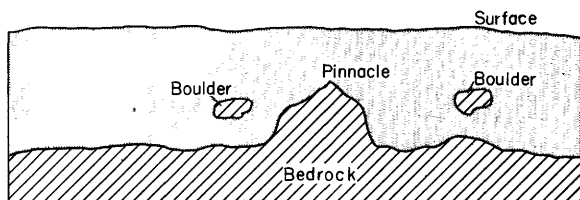

Figure 1. —Diagrammatic section to show a common relationship between soil cover, bedrock pinnacle, and boulders in Massachusetts.

incorrectly called the "velocity of the material") at which the impulse, or wave, travels through a given material depends upon its inherent elastic properties and its bulk density, or compactness. Of most rocks involved in highway construction problems, it may be said that the more compact or denser the material, the faster the wave travels through it. By sending an impulse through the ground and recording it for definite successive points on the ground surface, we can measure the time of travel through the material, providing we also have an adequate time-recording instrument, or seismograph. Thus, the seismic instrument consists of a time-recording device and a number of seismometers—also called pickups or "jugs." The pickups are placed at measured intervals along the ground, and each is connected electrically to the recording instrument. The impulse is provided by exploding dynamite in the ground at one end of the line. As the impulse reaches each pickup it is recorded separately on a

moving photographic ribbon in the recording instrument. The ribbon and timing mechanism are, of course, properly synchronized and calibrated. We can then plot the distances and arrival times for each pickup, and so determine the speed index for the material. The plot looks like the solid line in figure 2. Obviously, the slower the impulse travels, the greater will be the times plotted on the graph while the horizontal distances will remain the same. This will give a steeper slope to the speed (so-called "velocity") line on the graph, as illustrated by the dotted line of figure 2.

Suppose we have two materials, one on top of the other, and that seismic waves travel faster in the lower one, as in figure 3. Pickups numbered 1 to 5 receive the waves from the upper material, the "hardpan," of low-wave speed. Thereafter pickups 6 to 12, the first waves received, are those refracted from the lower, denser, higher-wave-speed
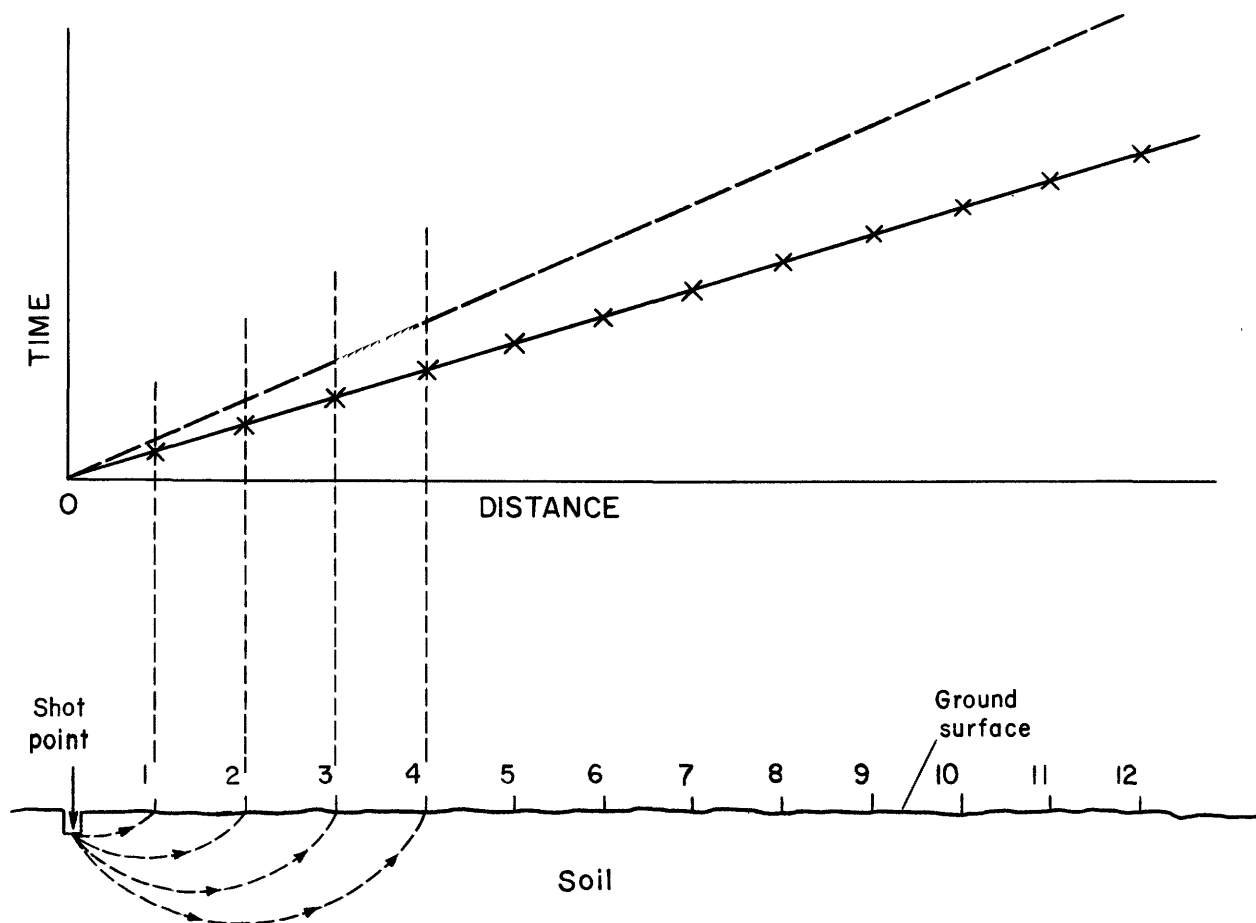

Figure 2.—Time-distance graphs (seismic speed graphs) for single, uniform, subsurface material. Speed of wave is indicated directly by the slope of the speed line, which is measured by $\frac{t}{d}$. Wave paths shown for first four detectors. Dashed line represents speed line for medium of lower wave speed.

bedrock. So we get a speed line for each of these two materials. They intersect at point d and the length of Ad'' is a mathematical quantity with which the depth to the bedrock surface at the shot point A can be calculated according to an established formula. This is the theoretical situation for the simple case of two uniform, homogeneous materials whose surface of contact is parallel with the surface of the ground.

Now, the seismic record may be read directly to the one-hundredth of a second, and interpolated to the one-thousandth of a second. Accordingly, if the wave speed in the upper material in figure 3 is, for example,
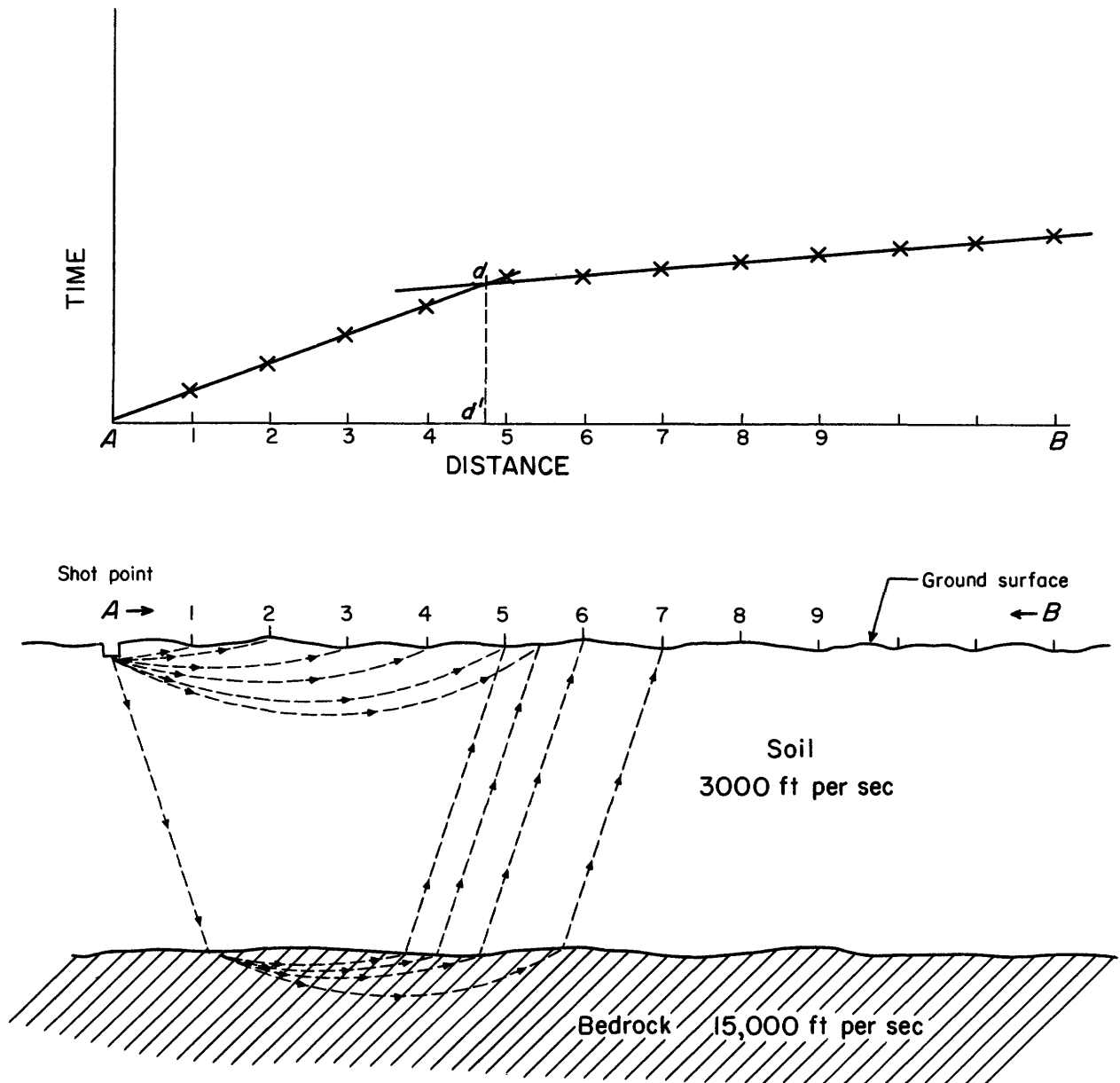

Figure 3. —Diagrammatic seismic speed curves for soil cover and bedrock where the bedrock surface is parallel with the ground surface. Soil and bedrock speeds assumed. Slopes of speed graphs are proportional to assumed speeds and are drawn to scale. Abscissa Ad' is a mathematical function of the depth to bedrock at point A, according to an established formula. Wave paths for first seven detectors ("pickups") indicated by dashed lines. Note that wave paths entirely in soil for five and beyond would not register owing to earlier arrival of higher speed waves from the bedrock.

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3,000 feet per second which is a common value for some engineering soils such as dry, bouldery sand and gravel, it would appear that the theoretical mathematical accuracy of the depth calculation is approximately 3 feet. However, since the length of the critical wave path includes return to the surface, or approximately twice the depth to the lower, denser material, the maximum theoretical accuracy of the depth determination would be approximately $1\frac{1}{2}$ feet. With surface materials of greater wave speeds the degree of accuracy is correspondingly less; for example, for a 6000 feet per second speed, the theoretical

accuracy could not be better than 3 feet. In no case would the theoretical accuracy of a single seismic test be better than 1/2000 of the wave speed of the upper material. The theoretical accuracy is, indeed, rarely attained, because of material variations in the soil layer, of irregularities in the ground surface and the interface, of difficulties in reading and interpolating the record, and of other operational factors.

Let us assume now that the bedrock surface rises from point A toward point B, as in figure 4. The impulses that pass along the
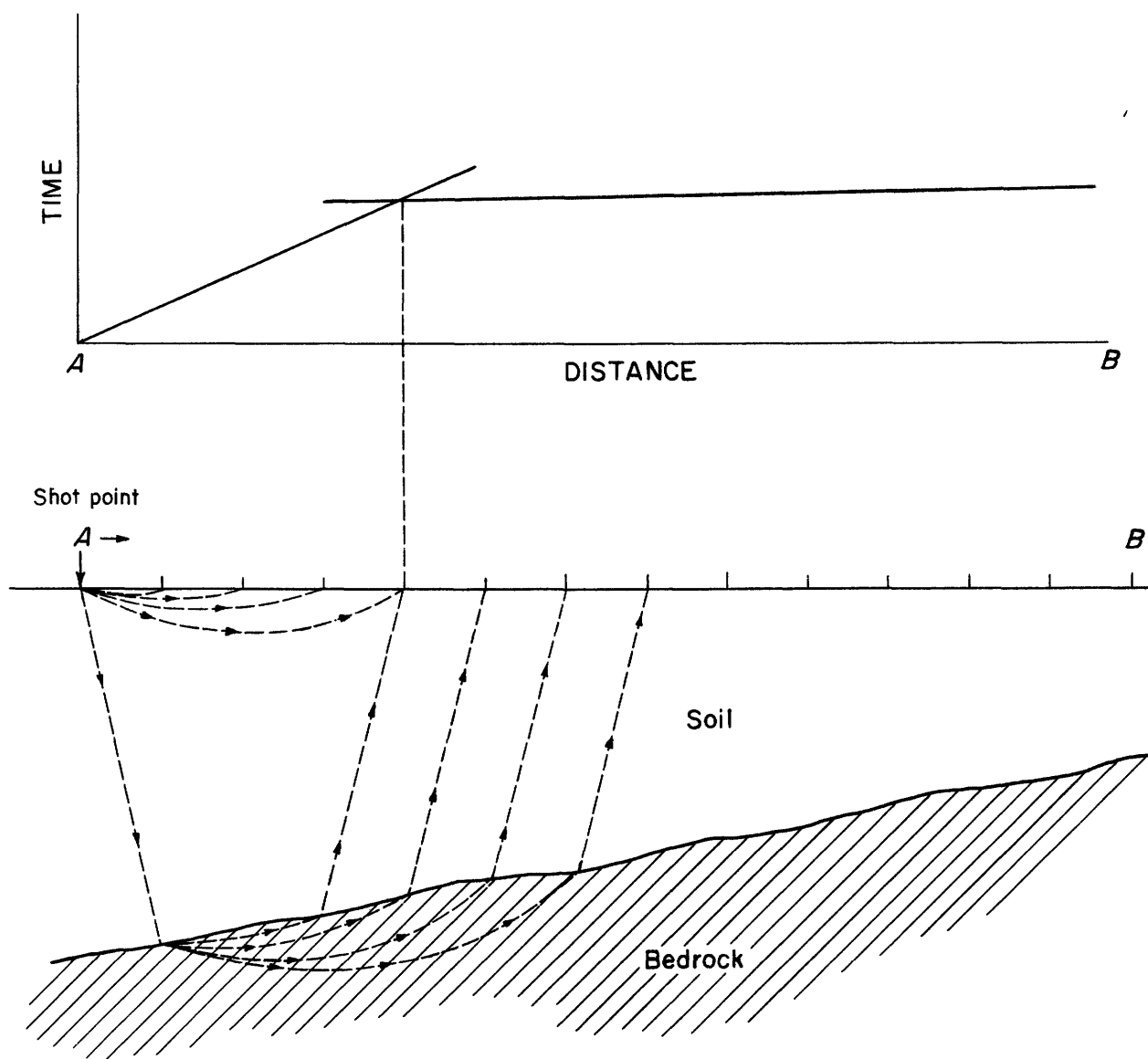

Figure 4. —Seismic graph (speed curves) for soil and bedrock where bedrock surface rises relative to topographic surface, from shot point. Wave paths for first seven detectors indicated by dashed lines. Note flatness of bedrock speed line as compared with figure 3, indicating abnormally high wave speed. See also explanation of figure 3.

bedrock and are refracted from it, are has-tened because they pass through less and less low-speed soil on their return to the pickups. The plotted speed line for the bedrock then has a flatter slope in the graph. This abnor-mally high speed for the bedrock tells us that from point *A* toward point *B*, the rock surface is rising, but it does not tell us by how much it rises. By "shooting" from point *B* back toward point *A*, however, we can obtain a bed-rock depth for point *B* —as we did for *A*—and so tie down the bedrock line at both ends of the profile, if the bedrock surface is not ir-regular. Incidentally we always "shoot" the reverse profile as a check of the interpreta-tion of bedrock slopes. Moreover, the total elapsed time for both profiles should theoret-ically be the same, or rather, within one one-thousandth of a second.

All this works out very nicely for the ideal case we have chosen, namely two uni-form and homogeneous materials, a uniform ground surface, and a uniform surface of bedrock. But these conditions are found rarely. The ground surface is not always. uniform and flat, the materials are never uniform and homogeneous, and the bedrock surface is generally irregular with knobs, depressions, pinnacles, etc.; moreover, even the bedrock material may not be homoge-neous. The result is that the points plotted on the time-distance graph do not fall ex-actly on a single straight line. Moreover a depression in bedrock will displace a seg-ment of the velocity line above the rest of the line, and a knob or pinnacle will throw a segment of the line below, as shown in figure 5. We must judge whether or not a displaced
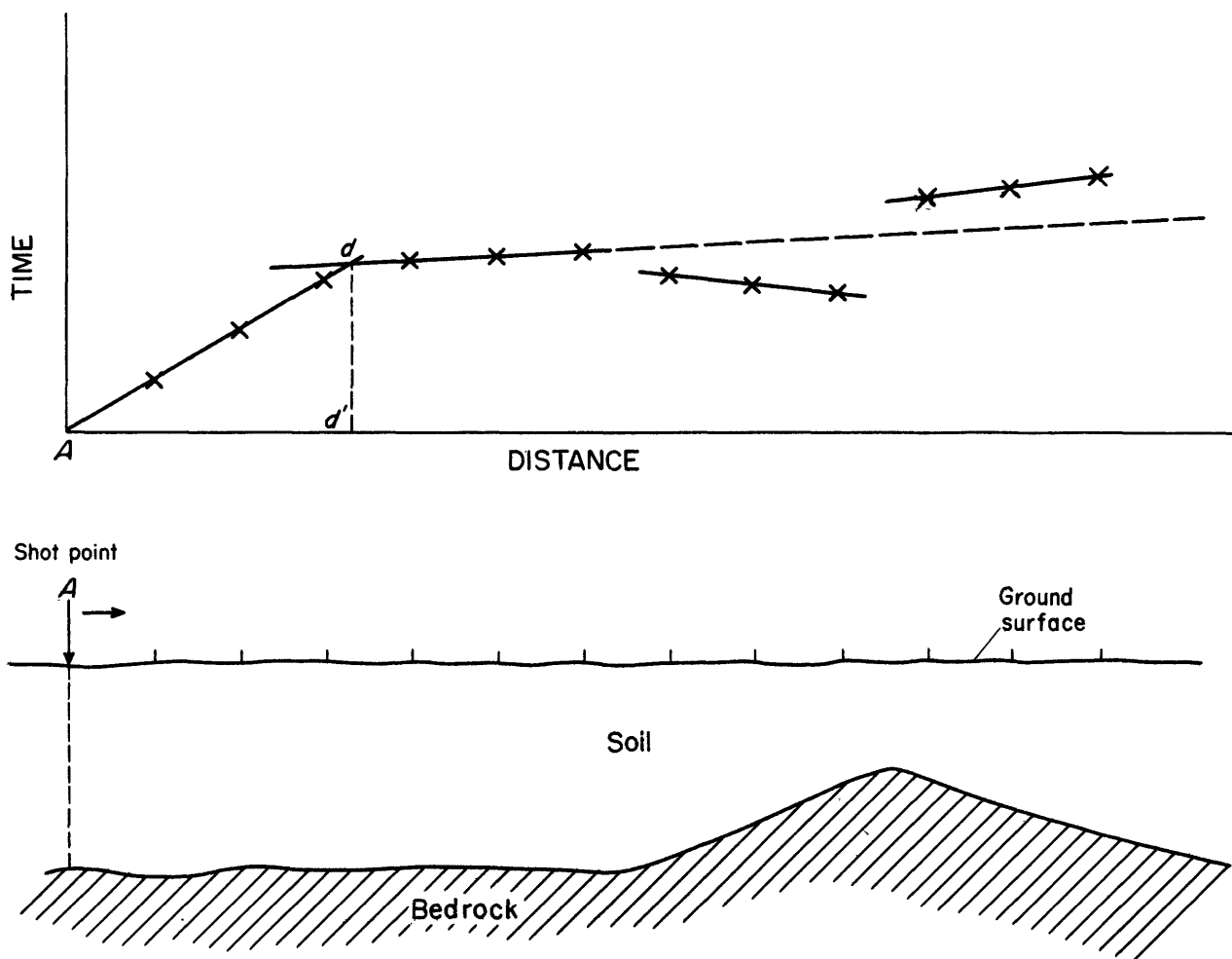

Figure 5.—Diagrammatic seismic graph to illustrate effect of changes in slope of bedrock surface on continuity of bedrock speed graph. *d'* has same significance as in figure 3.

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point on the graph is anomalous or signifi-cant.

Now you can see how complications arise in the interpretation of seismic data and in the determination of depths to bedrock. But this complication of irregular bedrock surfaces is only one of several. Others include: variations in the internal structure of the materials, which, let me repeat, are rarely uniform; relatively low speed values of some kinds of rock, such as shale and some mica schists, that may not be appreciably different from the true speed values of some very compact soil material; and partly disintegrated upper parts of bedrock, causing a lower speed value than is normal for the fresh, solid bedrock. Also, the speed value across the layers of schist-rock may be much lower than that along the layers. Finally, large blocks of rock or nests of boulders in the soil material are not certainly detectable, although they sometimes affect the apparent speed value of the soil to a minor degree.

The effective depth of penetration of the impulse and hence the depth from which a bedrock surface may be detected, is a function of the length of the seismic traverse line. To record depths of 100 feet will ordinarily require a traverse line about 330 feet long. This permits a 30-foot spacing for the 12 pickups. A knob or depression of appreciable size would not be detected by such spacing unless one or more pickups happened to rest directly above it. These features can be found by placing the geophones closer together and shooting segments of a traverse. This, of course, increases the time and expense involved in making a single traverse. It is clear, therefore, that the length of the seismic traverse should be chosen according to the approximate depth to bedrock, for best results. Inasmuch as the depth is what we are trying to determine, it is sometimes necessary to repeat a traverse at a site, using different spacings, and perhaps a different orientation.

The contractor has to consider large or nested accumulations of boulders as bedrock, or to use the engineering term, "ledge," in estimating excavation costs. The geologist cannot yet identify hidden large boulders or boulder concentrations, though in some instances he may suspect nests of boulders from anomalies in the seismic record. We

are working on this problem. So there is a difference in definition between the geologist's "bedrock" and the contractor's "ledge." In subsequent comparisons between seismic predictions and actual excavations, this difference in definition must be recognized. It probably represents the area of greatest and most common discrepancy between subsurface seismic profiles and what is actually found as "contractor's ledge" when the excavation is made.

Obviously, also, when you try to draw a subsurface profile for a section line that is situated away from a seismic traverse, or that lies between two seismic traverses, you introduce another possible error, for the seismic profile indicates the probable conditions only along the seismic traverse line. Unless you know that the bedrock surface is regular, you cannot assume that the nearest seismic profile or profiles can be safely interpolated to the offset or intermediate line. A depression in the bedrock surface, or a knob may intervene. By the same token a remote wash boring may reach an unrelated refusal or reflect only a strictly local variation in soil materials.

So far I have considered only two-layer problems. When there are three layers of wave speeds increasing with depth—such as dry sand, "hardpan," and solid rock—there are three speed lines on the graph to be interpreted. A corresponding complication is introduced into the interpretation. The principles involved are, however, similar.

You may ask, then, and quite properly, if it is worth while to make seismic tests, when such inaccuracies and difficulties are inherent in the method. We would reply that seismic tests provide the best available practical guide considering the time and expense involved. We have made many comparisons between seismic profiles and the actual conditions disclosed by excavations. We have found that approximately 85 percent of the profiles have been satisfactory. This includes the places where the bedrock surface clearly lies below the proposed depth of the excavation. We have found also that most of the serious errors result where the bedrock surface lies at a very shallow depth. As a result of our experience we do not recommend the seismic method for depths under, say, 10 to 15 feet, despite the fact that we have had some

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very good results with such shallow depths. That the refraction seismic method is of practical value in subsurface exploration of highway and bridge sites is attested by the high incidence of satisfactory results as compared with wash borings and site "guess works." It is also attested by the increasing use of the method elsewhere. The seismic method is not new; the reflection method has long been used in the petroleum industry for determining deep structures, and both reflection and refraction methods have been used in studies of the earth's crust. Use of the refraction method for shallow depths and short traverses in highway engineering projects and for foundation sites is a comparatively recent development. In Massachusetts we started to use it on highway sites in an experimental way in 1945. So far as I know this was essentially a pioneer effort. Several states now use it extensively.

A seismic profile permits an interpretation of the bedrock surface along a line between shot points, whereas a wash boring or a core drilling provides no data beyond the point at which it is made. It would take many drillings, at much greater expense, to give the same amount of information as a single seismic traverse. Though appreciably less accurate,

the seismic traverse generally gives practical results within a reasonable range of accuracy. But the method must be used with a complete understanding of its limitations as well as of its advantages. A line that is designated as a seismic bedrock profile should be considered only as a guide. In many places it needs support by surface geologic surveys, wash borings, core drillings. The data must be interpreted by a geologist who is familiar with the regional as well as the local geology. Everything considered, the method is the most satisfactory procedure for preliminary subsurface exploration of highway sites. As you have seen, it is not infallible but it is highly practical considering the time and money involved, especially when supported by collateral data.

Improvement is clearly needed in seismic technique and interpretation procedures used in solving shallow exploration problems. That fact does not vitiate its present usefulness, but it does point up a field of needed research directed to greater overall accuracy of interpretation and correlation of abstract seismic data with specific geologic materials and structures. Our long-range plans include such research.