this program are made by Rev. Daniel Linehan, S. J., of Weston College, Weston Massachusetts.

It is recognized that the work done under this cooperative arrangement since its inception in 1944 has been of an experimental nature and that conclusive results cannot yet be drawn from this research, but it is felt that a progress report of these activities will be of present interest. With this in mind a brief statement follows, giving in turn the approach of the geologist, the seismologist, and the highway designer to the application of geological and seismological research to highway location and design in Massachusetts.

GEOLOGIC METHODS AND INTERPRETATIONS

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In the design and construction of modern major highways the engineer faces a diversity of problems. These are in considerable measure concerned with the topographic characteristics of the terrains, and the physical properties and structures of the underlying materials. In the days of narrower and lower-speed highways there was greater latitude in choosing a road site. Today the highway route must be as direct as possible, and the design must meet all the requirements of modern highway standards, with curves of adequate sight distances, easy grades, and well-drained foundations capable of sustaining heavy traffic loads. To fulfill these requirements, less favorable topographic features must be traversed rather than avoided in many places, so that deep and wide cuts, and long, heavy fills are frequently necessary. Costs of excavation are greatly increased because many of the cuts penetrate well into bedrock, and costs of filling rise with the greater volume of suitable material to be provided often obtainable only at a considerable distance from the fills. In places, as in boggy areas, unsuitable materials must be removed and suitable ones substituted. Shallow or perched water tables may exist and require special construction to provide good subgrade drainage. Footings of heavy bridge piers must in places be spread in soft or even plastic materials instead of on sound bedrock; in the design of such piers it can be advantageous to know if bedrock can be reached economically, or if the overlying unconsolidated material is uniform and can adequately support the loads to be imposed. Thus the engineer is faced with problems of design and construction that involve many geologic factors. We are concerned, therefore, with the techniques of the engineering geologist insofar as they can contribute valuably to the analyses and solutions of the problems, or facilitate the work of construction. The engineer is not ordinarily prepared by either training or experience to make geologic interpretations.

A land mass that has been subjected to uninterrupted weathering, erosion, and deposition through geologic time normally develops a soil mantle and topography that bear certain clear relations to each other and that reflect the local subsurface rock structures and materials. The mineralogic composition of a residual soil formed under such conditions is consistent with that of the underlying rock from which it was derived. Except where it is a residual from impure limestone, or other less common soluble formations, the soil grades from unconsolidated material at and

near the surface through a transition zone into solid rock. In such places, the, the contact between the bedrock and the derived soil is not sharply defined. The thickness of the soil zone, too, varies with the lithology of the area, the depth of the ground-water table during the formation of the soil, and other geologic factors, but the variations follow a consistent pattern with respect to the topography and lithology, so that many of the local engineering problems have geologic factors that are resolvable in fair measure through accumulated experience in the terrain. Without much formal knowledge of the geology, the engineer of local experience can often interpret the features and predict what subsurface conditions he will probably find. He may be able to project his experience from place to place over a considerable area with reasonable assurance, according to his store of knowledge and the keenness of his powers of observation, even though he may not be able to describe his data in established geologic terms. When finer details of interpretation are needed, he must call upon specialists, but many of the simpler problems of the terrain he is able to solve for himself because the geologic phenomena are gradational and are integrated according to a consistent regional pattern; it is this "pattern" that he may learn to sense through experience.

In an area where former continental ice sheets have transgressed, however, as in New England, the normal integrated cycle of weathering, erosion, and deposition has been interrupted and the characteristic land forms have become disordered, so to speak. The thick ice sheet moving across the region covers both hills and valleys. Commonly its thickness is from a few hundred to several thousand feet, so that the pressure at its base is considerable. The ice sheet picks up or pushes along the loose soil mantle, scrapes the bedrock clean of its previously decomposed and disintegrated surface layers, and further abrades the bedrock itself. The materials picked up or pushed along by the ice includes particles that range from clay sizes to large boulders or blocks plucked from rugged ledges. The rock debris is so mixed up that, when later left in place by the melting ice, the components of the resulting heterogeneous soil layer may no longer accurately reflect the underlying bedrock formations. The material at a given point may have been derived in large measure from a distant area. Such unsorted glacially deposited material is known as *till*, and may have been drived from many bedrock formations, local and distant.

Glacial erosion broadens and deepens preexisting bedrock valleys and steepened their sides. It reduces and rounds hills and ridges. The meltwaters pick up abraded material incorporated in the ice or heaped beneath it, and sort and transport it so that gravel, sand, silt, and clay are deposited along the glacial stream courses. Thus outwash plains are formed over the valley floors in front of the ice sheet. Deltas and lake-bottom deposits form in temporarily ponded areas. Long sinuous ridges of gravel and sand may be left within broad valleys and mark the positions of streams that flowed between the ice walled channels. High-perched terraces may line the valley walls where they were deposited between the walls and the sides of an ice tongue. It follows, therefore, that glacial deposits characteristically rest with sharp contacts on fresh, hard bedrock, or on other glacial deposits, in contrast with the gradationally zone between soils

and bedrock in a nonglaciated area, as described above. Finally, among the effects of glaciation that may be of great importance to the engineer is the disarrangement of the drainage pattern. Valleys are filled partly or are blocked, and the postglacial drainage lines frequently do not follow the courses of the preglacial channels. Entirely new channels may be cut along the paths even of major streams that have been locally displaced; these new channels are commonly cut into bedrock, with the preglacial channel lying buried somewhere in the vicinity. Thus the effect of glaciation is to obscure the orderly results of the earlier normal erosion cycle.

The engineer who is untrained in the applications and techniques of geologic science is, therefore, not only unable to project his local experience from point to point in a glaciated area with reasonable assurance, but many times he cannot interpret even the local soils and rocks with sufficient certainty; it is the third dimension that is not disclosed to him, and it is the variation in this vertical dimension of the terrain with which he is particularly concerned. The surface deposits may be misleading, the soil zone greatly variable even within shallow depths, and hidden boulders may, and often do, mislead or confuse him with regard to the position and nature of the bedrock. It is true, of course, that the geologist cannot always make accurate interpretations from surface data alone, but must rely on some other techniques; nevertheless, even where surface data are inconclusive to him, the geologist's guess is considerably better than the engineer's, and is based on laws of geologic probability as suggested by the local surface geology. He is, by virtue of training and experience in his science, in a far better position to make directive interpretations and give warning of probable or possible difficulties. He should, in general, be better equipped to work with specialists in the fields of seismology and soil mechanics, and, indeed, should be in a position to advise when such collateral services are needed or desirable; moreover, he should not be reticent or hesitant in recommending such services.

The common impression that geology is an inexact science arises largely from the fact that geological phenomena are generally gradational through all degrees and between wide limits. Appreciation of this fact is necessary if the science is to be used to its maximum benefit. For the most part, however, it is neither the geologic concepts nor the geologic techniques that are inexact; rather it is the variability of the phenomena and difficulty in obtaining enough exact measurements that make it appear as a qualitative science. But even if the engineer approaches it from the qualitative viewpoint he can find it very useful, particularly in the preliminary and planning stages. It is a serious mistake for him to disregard the concepts and teachings of a science whenever its techniques do not justify the use of the slide rule or calculation of its physical data with "engineering accuracy." It is worse than futile - it is misleading - to report data to a fraction that is measurable only within units. Much of the geologic data usually acquired is of this nature, though the techniques employed are capable of considerably greater refinement. To recognize these techniques, then, and to bring them into the formative stages of the engineering project is as much the duty of the engineer as it is the

duty of the geologist to evaluate his own methods and apply them with appropriate care.

The physical features of the terrain, that is, the topography, rocks, and soils, are elements that may be analyzed by the special techniques of the geologist and the soil scientist. These technicians, therefore, are able to supplement and aid the work of the engineer by furnishing pertinent physical data are not otherwise available to him. It seems axiomatic that insofar as these special techniques can furnish such data they should be available in the preliminary stages of highway location and design. As these techniques advance through experience and research they should be under constant critical scrutiny so that their potential usefulness may be recognized. The geologist and the soil scientist should each know his own limitations as well as each other's, and should be able and ready to advise where the use of other techniques may be helpful. as in the field of seismology.

The geologist's aim is to call the attention of the engineers to the kinds of data available through geologic techniques, and to make such data as directive and quantitative as possible. It is helpful if he knows something about the technical methods of the engineer, but he should not presume to advise in purely engineering methods. Upon the engineer, on the other hand, rests the responsibility to seek and use all available data that will contribute to sound and economic design or construction of highways and bridges. This, then, is the philosophy that determines the pattern for engineering geologic work under the Massachusetts program.

The Massachusetts geologic program was started in July 1938, as a cooperative project between the Massachusetts Department of Public Works and the U.S. Geological Survey. The primary and principle purpose is to make a complete and detailed geologic study of the State, the results of which are to be embodied in two geologic maps and accompanying brief reports. The maps are to be printed in colors. One of them is to show the distribution and structures of bedrock units beneath the soil mantle, as interpreted from bedrock exposures and available subsurface data; the other is to show the distribution and nature of the unconsolidated, superficial formations, the "soils" in an engineering sense, that overlie the bedrock, and also to show the actual bedrock exposures. Among the mineral resources to be indicated on these maps are the materials used in highway construction, such as gravel, sand, rock for crushed stone, and so forth. Mapping is being done by quadrangles, on new 7½-minute topographic base maps, the scale being two inches to the mile and the contour interval 10 feet. These maps permit considerable detail and accuracy, and engineers and geologists engaged in either public or private work will thus have fundamental geologic control for their own more detailed work in small areas or on special problems. Two compiled geologic maps of the State will be prepared from the quadrangle maps, on a scale of 1:125,000, or about ½ inch to the mile.

Special geologic studies are made under the program at the specific request of the project engineer of the Department. These studies are of four types, as follows:

1. *Gravel and sand resources of particular areas.* For areas of projected highways where the resources are as yet unknown, or the known deposits are unavailable or inadequate, detailed geologic maps are made to show the distribution and

land forms of all deposits of sand and gravel. An accompanying table indicates for each potentially important deposit the approximate volume, areal extent, dimensions, accessibility, and type of material. Pertinent general observations are made regarding the quality of the material, pebble sizes, proportion of sand, freshness of the pebbles, and probable utility. No grade-sizing tests are made, as these are considered to be outside the province of the geologic program. The map is intended as a guide to point out apparently favorable deposits for further investigation by engineers of the Department.

2. *Reconnaissance geology* When a segment of a proposed highway has been located by engineers, a detailed geologic map is made along the centerline for the purpose of determining the kinds of materials, the geologic structures that may have a bearing on engineering operations, and the distribution of bedrock outcrops (see Figure 1). Usually, the reconnaissance strip so mapped is from a quarter to half a mile wide, but may be greater or less according to the complexity of the area and the need for finding additional data to aid in the interpretation of the geology along the centerline. A brief report summarizes the geology and calls particular attention to features that may prove troublesome. Where the geologic data appear to be clear and unequivocal no further studies are made. Where geologic conditions are complex or obscure, and more specific data are needed, other kinds of studies (such as ground-water investigations or seismic tests) are indicated by the geologist. Occassionally this preliminary reconnaissance study leads to a consideration of other possible locations for the highway segment. It is always desirable to have an engineer review the strip in the field with the geologist; in this way interpretations are clarified and pointed up, the geologist becoming more acute with respect to the engineer's problems, and the engineer learning how to use the geologic data with greatest profit and to judge the limitations of geologic studies.

3. *Ground-water investigations* The highway engineer is concerned with ground-water conditions along the highway site because of the effects of ground saturation and seepage upon the stability of the subgrade, especially in freezing weather, or upon the walls of cuts that have reached to or even penetrated the local water table. Perched water tables are quite commonly found in glaciated regions where lakes have once existed. Even certain types of compact till overlain by loose till or sand and gravel are so impervious as to cause seepage into the walls of a cut during the more humid seasons. The engineer wishes to foresee such conditions and to provide for adequate drainage. The conditions vary from place to place and the variations are direct functions of the geologic materials, structures, and topography. In places the possible effects on highway construction of local ground-water supplies and individual wells present problems that require study by ground-water specialists. When necessary, ground-water problems are referred to geologists of the Ground Water Division of the Geological Survey, working also under a continuing cooperative program with the Department of Public Works, for ground-water studies in the Commonwealth. Separate reports or statements are prepared by this Division upon request of the supervising geologist.

4. *Seismic studies* Where more exact knowledge of the subsurface materials, and especially the depths

to bedrock or compact, hard till is needed, seismic tests are recommended by the geologist. The details of the seismic operations and the fundamental theory of the technique are described in Part II of this paper, by Rev. Daniel Linehan. In brief, the method determines the velocities of explosion shock waves in the successive subsurface media, and from these velocities and their variations are interpreted the general characters and depths of the materials. The method provides physical constants of the media, and because the materials vary in their physical properties and the ranges of these properties overlap, their interpretation in geologic terms must be made with a knowledge of the geology of the general area. It is necessary, therefore, for the geologist and the seismologist to work in close cooperation, so that the data obtained by each may be coordinated. The preliminary geologic study of the highway strip furnishes the necessary background, inasmuch as the seismic locations are recommended as a result of the geologic study, but the geologist also accompanies the seismologist in the field when the seismic work is done so that controlling interpretations may be made on the spot, when necessary, and changes made in locations of profiles, or additional profiles recommended. A joint report is prepared by the geologist and seismologist.

The seismic method is used primarily to determine depths to the bedrock surface, and to interpret the probable profiles of this surface along the line of traverse. The depths to bedrock are determinable only for the ends of a traverse, at which points the explosive charges are set off. The variations of the wave velocities between these points will, however, indicate the slope and changes in slope of the rock surface relative to the ground surface so that the seismologist is able to interpret a complete profile of the bedrock surface between the ends of the traverse. By using a sufficient number of seismic detectors and choosing the proper spacing for them a considerable amount of detail may be obtained. The closer the spacing of detectors the more detailed will be the data, but in some places, where the bedrock surface is very irregular, the data obtained by close spacing may become very complicated and the bedrock irregularities may be interpreted with less clarity than the general slope of the surface. Using the profiles plotted by the seismologist, the geologist completes the geologic section along the traverse by interpreting the materials on the basis of his local geologic studies. In places it is possible to interpret, from coordinated seismic and geologic data, several successive layers, such as loose sand on clay on bedrock, or loose till on compact till on bedrock. Figure 2 illustrates geologic sections interpreted upon seismic profiles for a specific highway location.

It has been standard practice to make a profile first along the highway centerline, and as needed to make additional parallel or cross profiles. A few locations have required but the single centerline profile together with areal geologic data to show that the bedrock surface is well below the proposed cut and the soil material is uniform. Where shallow bedrock is indicated by the centerline profile, however, and probable variability is indicated by the surface geology, additional profiles are agreed upon by the geologist, the seismologist, and the engineer, to satisfy their individual requirements for control data. Where it is desired to plot

COMMONWEALTH OF MASSACHUSETTS
DEPARTMENT OF PUBLIC WORKS

COOPERATIVE GEOLOGIC PROJECT

U. S. DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GEOLOGIC RECONNAISSANCE ALONG A PROPOSED HIGHWAY SEGMENT RELOCATION OF ROUTE 2; LEOMINSTER, MASSACHUSETTS.

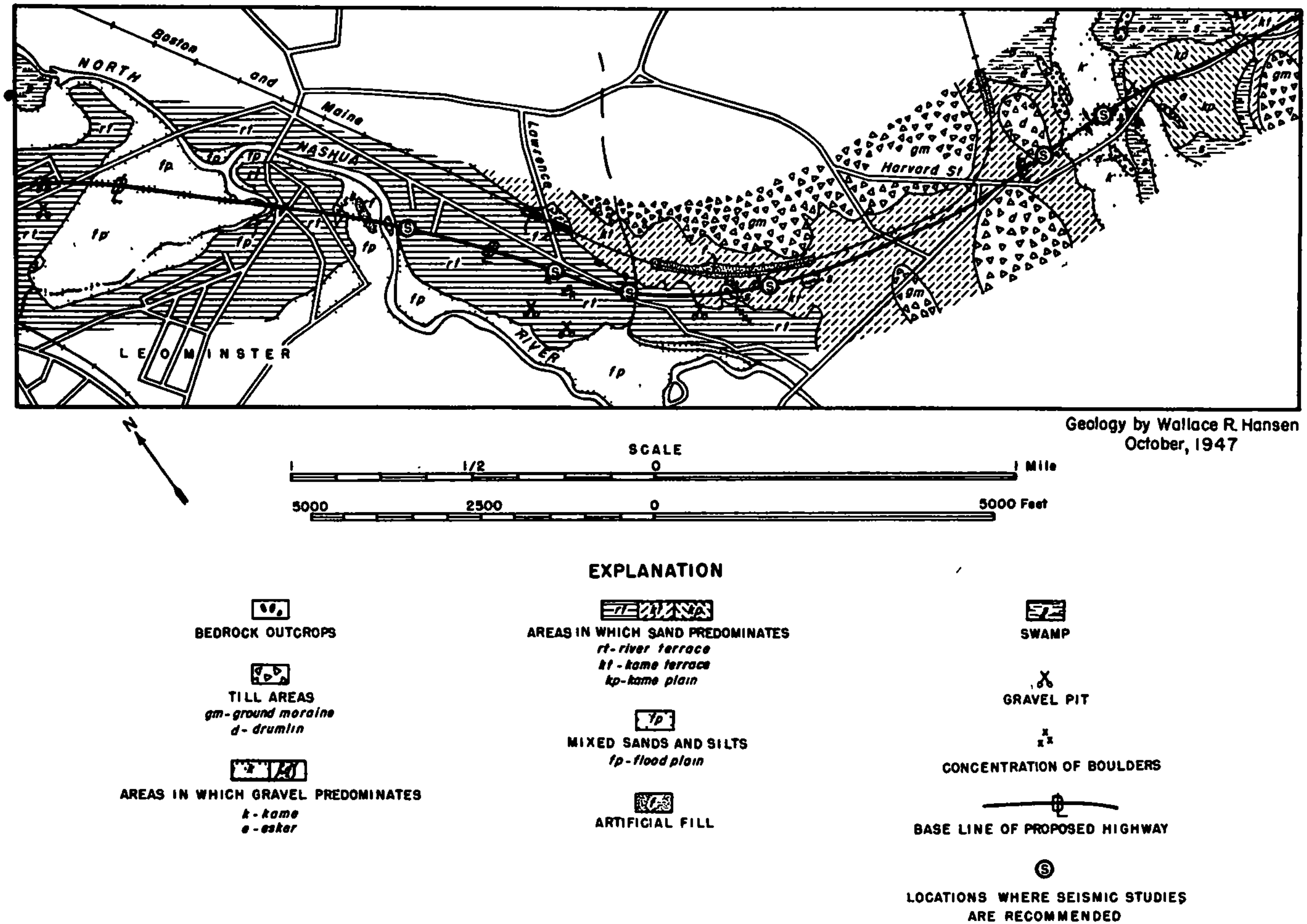

Figure 1. Geologic "strip" map showing distribution of soil materials, bedrock, and land forms along a segment of a proposed highway location.

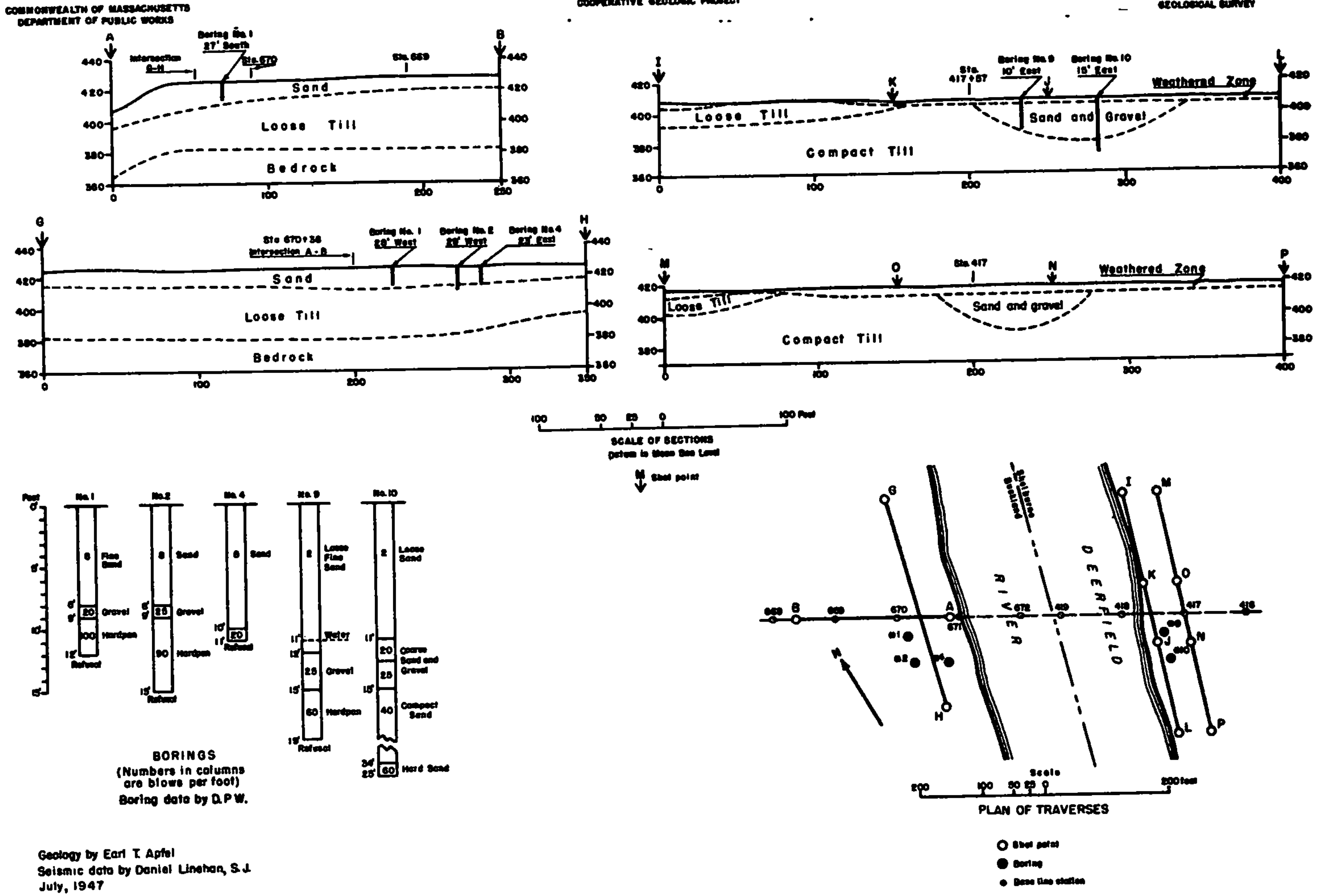

Figure 2. Interpretative Geologic Sections Along Seismic Traverses, Showing Correlation With Boring Data: Relocation Of Route 2, Deerfield River Crossing; Shelburne-Buckland, Massachusetts

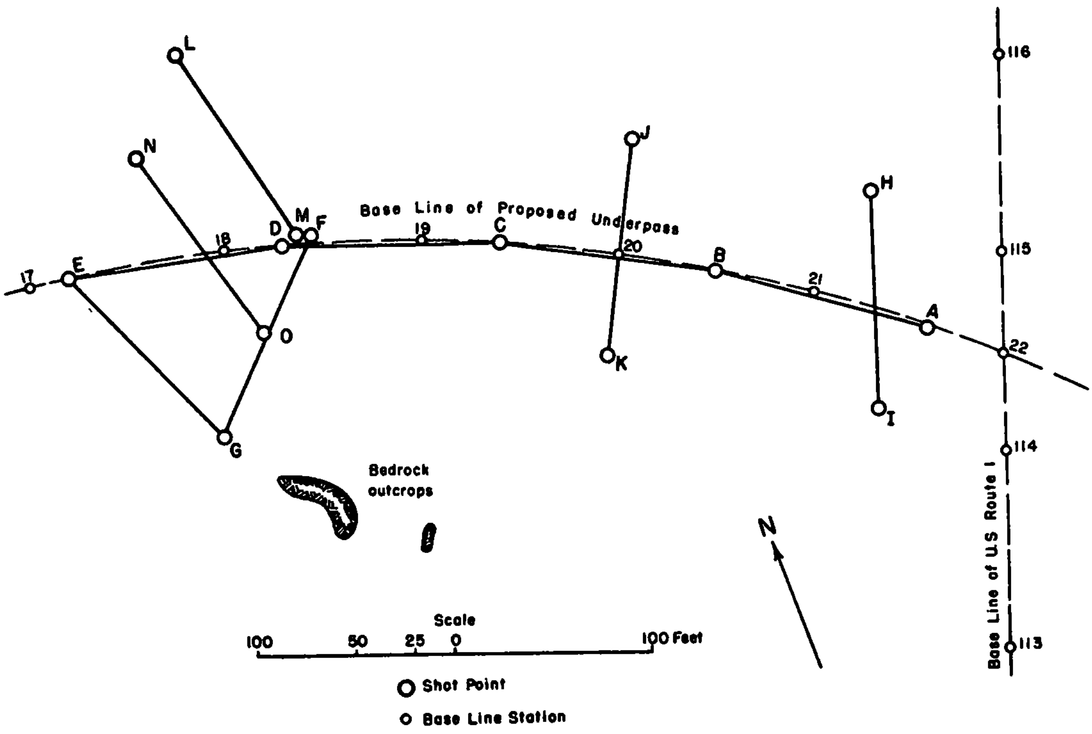

Figure 3. Plan Of Seismic Traverses At Proposed Underpass Of Route U. S. 1, Peabody, Massachusetts

contours of the bedrock surface, additional profiles are made to give an areal spread of actual depth determinations. At bridge sites traverses have been arranged in T-shape on both sides of the river; this arrangement gives several depth determinations at the pier locations, and the slopes of the bedrock surface along the centerline. Cloverleaf underpass locations may require a considerable net of traverses (see Figure 3).

Wash borings have commonly been used to determine subsurface conditions and materials; "refusals" in such boring, however, are commonly unsatisfactory, because there is no discrimination between refusal due to a boulder and one due to bedrock. Numerous borings may be required to distinguish a large glacial boulder from bedrock, but a single seismic traverse will indicate whether or not refusals along a line of borings are due to one or the other. Thus the seismic method is of considerable value for interpreting boring data and controlling or limiting the choice of bore-hole locations.

Seismic methods have been used for a long time in deep subsurface exploration, especially by the petroleum industry, but the application of the seismic refraction method to such shallow-depth studies as are involved in highway engineering is believed to be rather a pioneer approach to the problems of highway location and design. There are certain difficulties to overcome and certain others that may not be resolved, but the technique is improving and has been decidedly helpful in many places. Experimentation is being carried on to de-

termine the optimum spacing of detectors and lengths of traverses for various purposes and terrain conditions. Further research is needed on certain particular application, as in some types of swampy ground, and areas in which the bedrock surface is very uneven. It is expected that some of the problems will be solved through the research that is being included in the Massachusetts cooperative program.