DEVELOPMENT OF GEOPHYSICAL METHODS OF SUBSURFACE EXPLORATION IN THE FIELD OF HIGHWAY CONSTRUCTION

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Since 1933 the Bureau of Public Roads, through its Physical Research Branch, has had in progress a study of geophysical methods of exploring the substrata as applied to highway engineering problems, including the development of instruments and of methods of interpretation of the data obtained. Early developments were reported in papers published in 1935 (15)[1] and in 1936 (17). Both earth resistivity and refraction seismic apparatus were adapted or developed for use in the shallow subsurface explorations usually associated with highway construction. Special attention was given to the necessity for portable units capable of being transported by hand into areas where reconnaissance surveys might be required. Figures 1 and 2 show respectively the seismic equipment and earth resistivity apparatus now in use.

A large amount of data has been obtained by the Bureau of Public Roads with this equipment applied to such problems as slope design, classification of excavation materials on grading projects, foundation studies for bridges, buildings and other structures, investigation of tunnel sites, location of sand, gravel, solid rock and special soils for use in construction, determination of depth of peat and muck in swampy areas, and studies of existing and potential slide areas.

These field studies have been carried out in the following States: Washington, Oregon, California, Montana, Idaho, Colorado, Arkansas, Missouri, Iowa, Michigan, New York, Connecticut, New Hampshire, New Jersey, Pennsylvania, Maryland, Virginia, North Carolina, Tennessee, Georgia, Florida, and in the District of Columbia.

In general, the data obtained have shown that both the seismic and the resistivity methods of test have merit, particularly as rapid and relatively inexpensive methods of exploration for use in preliminary surveys. As a result of demonstration work done in the States of New York, Connecticut and New Hampshire, the Corps of Engineers, US Army, adopted the seismic test as a more or less standard procedure in preliminary subsurface explorations in connection with investigations of possible dam sites for flood control. Hundreds of dam sites have been investigated by this method since the latter part of 1938 (19, 21, 23).

World War II caused curtailment of the use of the geophysical methods of exploration with the general decrease in civilian construction, but an increased interest is being manifested at the present time. The New York Department of Public Works has purchased equipment of both types and has assigned personnel to a continuing program of geophysical test as apart of a regularly instituted program of subsurface exploration. The geophysical work has been in progress since the early part of 1948, and it is hoped that reports of the successful application of both seismic and resistivity tests to the solution of construction problems within the State of New York will be made available in the near future. The Pennsylvania Turnpike Commission has kept two earth resistivity parties in the field since July 1948 in a systematic resistivity survey of well over 100 mi. of right-of-way for extensions to the present Turnpike system. The Michigan State Highway

[1]Numbers in parentheses refer to a list of references at the end of this paper.

Department has purchased resistivity apparatus for use in locating construction materials and on other construction and maintenance problems of that State. The Massachusetts Department of Public Works has had in progress since 1944 a program involving the use of refraction seismic tests in studies of highway grading projects and structure sites in Massachusetts. A report on this work was made at the 27th Annual Meeting of the Highway Research Board (29). The States of Wisconsin, Minnesota, Missouri, California, Texas and Illinois have each had some experience in the application of earth resistivity tests to highway construction problems (5, 9, 10, 14). The State highway departments of Georgia and Arkansas have expressed an active interest in an early application of earth resistivity tests to construction problems peculiar to their respective States.

With this brief summary of the present status of geophysics as an integral part of our highway construction program, it may be of interest to review briefly the theoretical aspects of the two methods of test and to consider in more detail their application in the field.

BRIEF DISCUSSION OF THE THEORY INVOLVED IN THE GEOPHYSICAL TESTS

Refraction Seismic Test[2] - The seismic method of subsurface exploration consists of creating sound or vibration waves within the earth, usually by exploding small charges of dynamite buried three or four ft beneath the surface, and measuring the time of

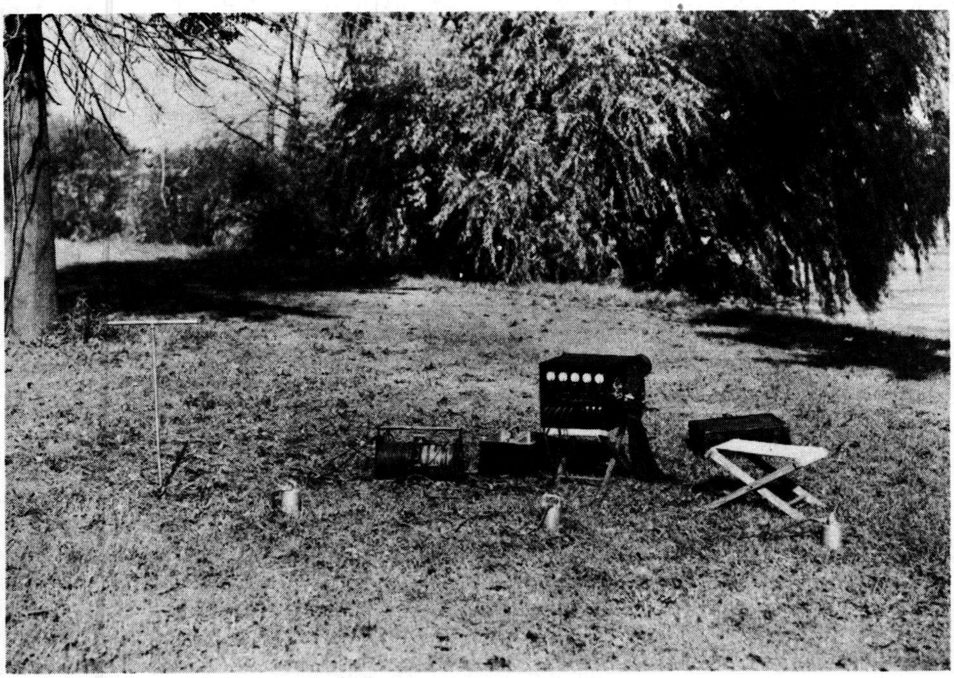

Figure 1. Refraction Seismograph Developed by the Bureau of Public Roads for Use in Shallow Subsurface Explorations

[2]For a more detailed description of the apparatus see reference 15, and for additional discussion of the interpretation of refraction seismic data, together with their application to various field problems see references 19, 21 and 23.

travel of these waves from their point of origin to each of several detectors placed at known distances from the source. The variation in mechanical energy transmitted to the detectors, or "seismic pick-ups" are converted into variations in electrical energy which, in turn, are used to deflect light rays reflected from small mirrors that are a part of sensitive galvanometers and these deflections are recorded

Figure 2. Apparatus Used by the Bureau of Public Roads in Shallow Earth-Resistivity Operations

photographically on rapidly moving film. Electrical circuits are so arranged as to obtain one impulse at the instant of firing the shot and another as the first wave reaches each detector. Figure 3 shows typical seismic records, the small break in the righthand trace on each film indicating the start of the wave and the three separate breaks in the three traces on each of the films shown indicating the arrival of the wave front at each detector. The space between the transverse lines on the film corresponds to a time interval of 0.005 sec. It is usually possible to estimate to one-tenth part of this time interval.

The time lines are placed on the film by means of a suitably placed light source and a tuning fork operating at 100 cycles per sec and equipped with thin phosphor-bronze plates on each tine having narrow slots which cause 200 flashes of light to reach the film during each sec of time.

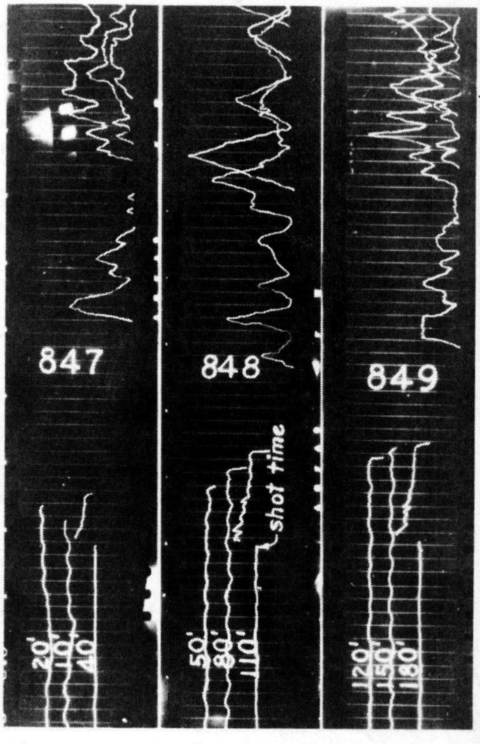

Figure 3. Typical Seismic Records - Note: For clarity in illustration the light traces were inked in before this print was made.

The time data obtained from film records and the measured distances along the ground surface, between the shot point and the detectors, are plotted in the form of time-distance graphs from which the depth and probable character of the various subsurface formations are determined. Wave velocities range from approximately 600 ft per sec in light, loose soils to about 18,000 to 20,000 ft per sec in dense solid rock. This wide range in wave velocities makes possible determination of the general character of the materials encountered and by use of simple formulas the average depth to the various substrata can be calculated. A knowledge of the local geology helps materially in a more accurate identification of the formations encountered.

Figure 4 to better illustrate the wave travel for short distances involving the low velocity soil and the longer distances in the rock stratum, only three detectors are required for the three-channel seismograph used by the Bureau of Public Roads. The usual procedure when using this type of equipment is to place the three detectors on the ground in a line and at intervals of 25 to 50 ft

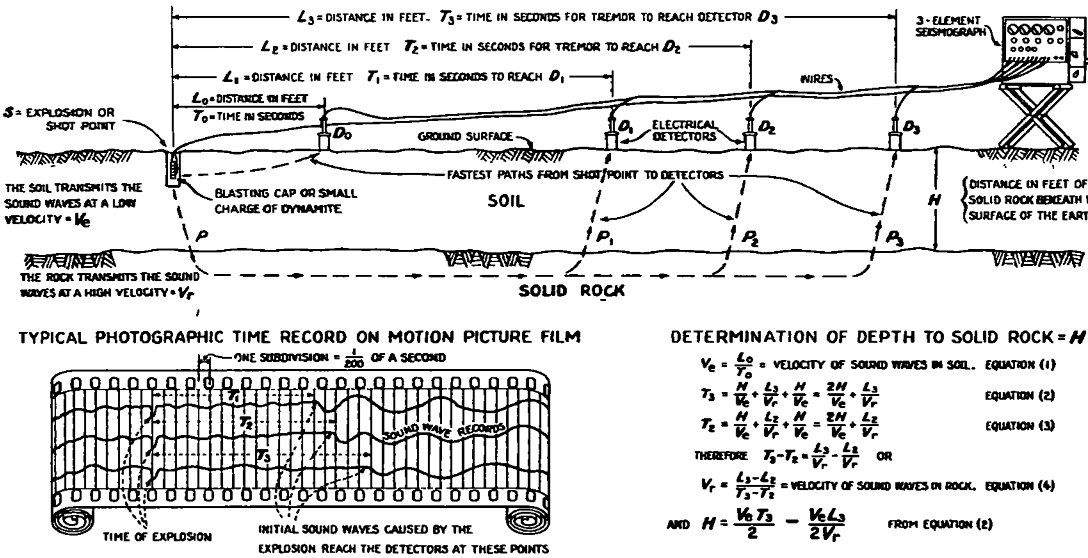

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Figure 4. Sketch Showing Fundamental Principles of Seismograph Method

The theory of refraction shooting and the derivation of approximate working formulas for depth determinations are shown in Figure 4. These equations, as will be seen, are developed on the assumption that the path of the seismic wave is vertical from the shot point to the rock or other dense stratum, thence along the rock to a point directly beneath the detector and thence vertical to the detector. Although this assumption gives satisfactory values for the shallow depths involved in most highway problems, it is preferable to use a more exact formula for tests to greater depths such as are encountered in exploring locations for dams and certain other structures. The derivation and application of these formulas may be found in published papers (18, 19) and will not be discussed further.

Although four detectors are shown in Figure 4 to better illustrate the wave travel for short distances involving the low velocity soil and the longer distances in the rock stratum, only three detectors are required for the three-channel seismograph used by the Bureau of Public Roads. The usual procedure when using this type of equipment is to place the three detectors on the ground in a line and at intervals of 25 to 50 ft apart. Shots are then fired successively at increasing distances along the detector line extended, beginning with a point 10 or 15 ft from the center detector and extending the shooting distances by increments to some greater value as, for example, 50, 85, 125, 165, 225 and 300 ft from the center detector. There is an approximate relation between shot distance and the effective depth of the test such that this depth is about equal to one-third the shot distance. The relation depends somewhat on the relative wave velocities in the materials involved. If the depth to rock were more than about 80 ft, additional shot distances greater than the 300 ft mentioned above would be required to adequately show a rock formation. A duplicate line of shots is usually placed in the opposite direction from the center detector to expand the data to allow depth determinations to be made when the interface between the overburden and the rock is not parallel to the surface but on a slope.

A theoretical time-distance curve is shown in Figure 5. As shown, a straight line through the origin will result so long as a uniform homogeneous material comprises the surface layer. The velocity of wave propagation is constant in such a medium and time of wave travel is proportional to travel distance. The reciprocal of the slope of the line, OC, passing through the origin, represents the velocity in the medium, since velocity is equal to distance divided by time.

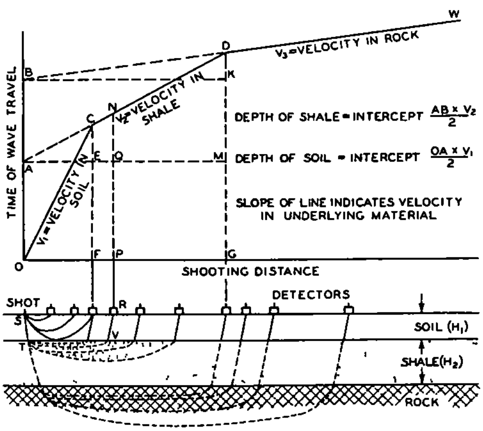


Figure 5. Time-Distance Curves from which Soil Profile Determinations are Made

If, at some greater depth, a second layer of homogeneous material of greater density is present, such as that designated as shale, there will be a point, F, at which there is a simultaneous arrival of a slower wave through the less dense surface soil and one traveling over the longer but faster route along the top of the shale stratum. Beyond this "critical distance", OF, a new slope, CD, exists, the reciprocal of which represents the faster wave travel in the shale, and for a path, STVR, the time, PQ or OA, is that required for the wave to travel through the surface soil from S to T and again from V to R. QN represents the time of travel from T to V in the shale. If H_1 is the thickness of the surface soil , we have the relation:

$$H_1 = V_1 \times \frac{OA}{2}$$

Similarly, for a third layer having an even greater density, such as that designated as rock, there will be a second "critical distance". OG, and a second break in the curve to a new slope, DW, the reciprocal of which will give the velocity in the rock. The time intercept MK or AB in this instance represents the time required for the wave to travel down through the shale

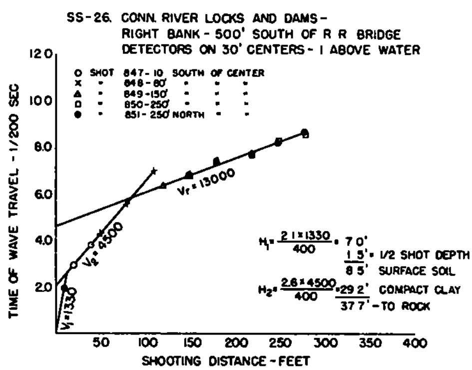


Figure 6. Time-Distance Graph for Seismic Records Shown in Figure 3

and back again. If H_2 is the thickness of the shale then:

$$H_2 = V_2 \times \frac{AB}{2}$$

Usually in plotting the time-distance data, the time units of 1/200 sec, as taken directly from the film records, are used and the denominator in the foregoing equations becomes 400 instead of 2.

When the geologic conditions existing at a particular test location actually approach those assumed in a theoretical analysis of the data obtained from refraction seismic tests, there is a remarkable similarity between the field curves obtained and the theoretical curve as it appears in Figure 5. This is illustrated by the time-distance curve shown in Figure 6 which was prepared from the field data shown in Figure 3, supplemented by two additional shots of electrolytic nature in which the moisture in the soils and rocks together with the dissolved impurities give to the several materials characteristic re-

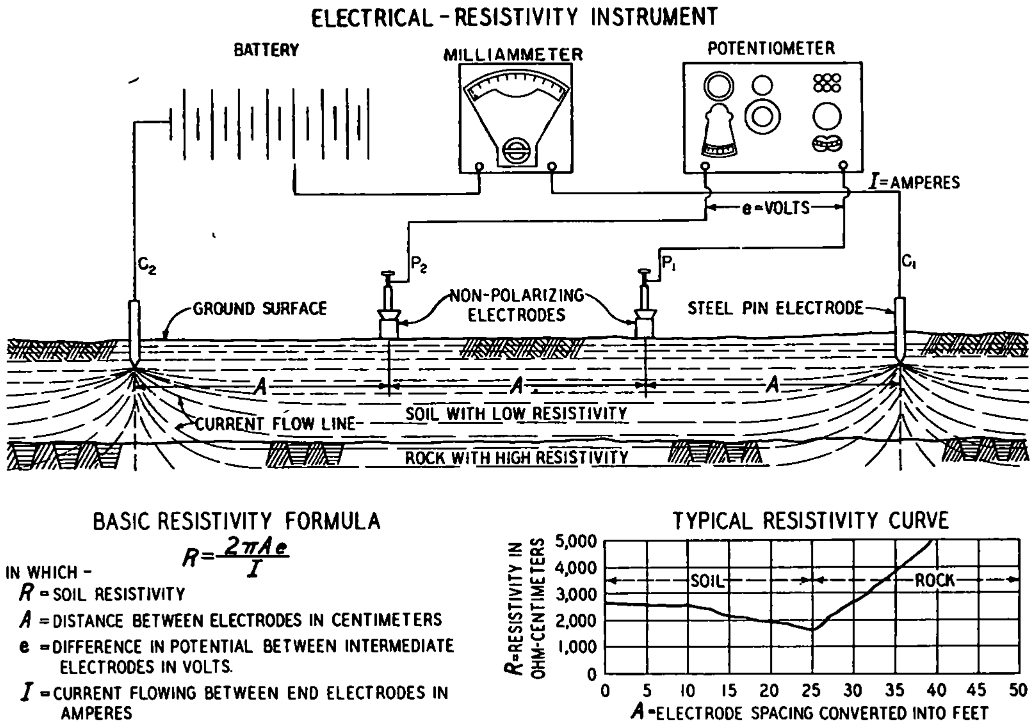


Figure 7.

placed at greater distances from the detectors. The data for this graph were obtained in New England where a relatively thin layer of loose soil was underlain by glacial till which rested upon solid rock.

Earth Resistivity Method [3] - Experience has demonstrated that many of the materials making up the earth's crust can be identified, in some degree at least, by their reaction to the flow of a direct current of electricity. This is an action

[3]For a detailed description of the apparatus and a more comprehensive discussion of the earth resistivity method of test see references 1, 3, 7, 15, 25 and 26.

sistances to a current flow. These characteristic resistances or resistivities may be used for locating and, to some degree, identifying subsurface formations. Figure 7 illustrates diagramatically the earth resistivity test and the Wenner electrode configuration (1) used by most investigators. In this test a prediction of the character of the subsurface materials is attempted by measurements indicating the magnitude of the resistance to direct current flow. Ordinary moist soils containing moderate amounts of clay or silt with some electrolytic agent more or less active, have a comparatively low resistance. In contrast, sand, gravel, extremely dry, loose soils and solid rock usually have relatively high resistivity values. However, these classifications are too general to be useful and it is very necessary to calibrate the instrument with tests made on local materials which can be identified by exposed faces, test pits, drill logs or other means. Curves obtained later for unknown conditions may then be compared with those for known conditions and a prediction can be made as to the materials lying below the surface.

Referring to Figure 7, an electric current is passed through the ground from a direct current supply, usually one or more radio "C" batteries, using the two outside electrodes. Measurement is then made of the potential drop between two intermediate points symmetrically spaced at the third points between the current electrodes as shown. The current flow is determined with the milliammeter and the voltage or potential drop with the potentiometer, from which the resistivity of the material is computed by use of the formula:

$$\rho = 2 \pi A \frac{E}{I}$$

in which A is the electrode spacing in centimeters, E is the potential drop in volts, and I is the current, in amperes, flowing in the circuit.

There is an empirical relation such that the "effective" current flows within a depth below the surface equal to A. That is to say, if A = 10 ft, the resistivity obtained with the formula represents an average of all material existing with 10 ft of the surface. Thus, as the electrode spacings of the system are expanded the current flow lines encounter the deeper portions of the underlying formations as, for example, a rock formation, as shown. This material, having an appreciably higher resistivity than the overlying soil, affects the average resistivity values, the effect of the lower bed increasing progressively as the tèst is carried to greater depths.

When using the empirical method of interpretation proposed by Gish and Rooney (2) the apparent resistivity, ρa, obtained by inserting the measured values of A, E, and I, from the field tests in the formula for resistivity as given above, is plotted as the ordinate against the electrode spacing, A, as the abscissa. The inflections in the resulting curve are interpreted as indicating changes in the materials underlying the surface. Where clay overlays rock a curve similar to that shown in the lower right-hand portion of Figure 7 is usually obtained. The depth of the surface soil is taken as the value of A (electrode spacing) at which the upward inflection of the resistivity curve occurs. This empirical solution has been used in analyzing data from many tests in the past. Cases were found, however, where the plotted curve was smoothly rounded with no inflection point, affording no criterion for predicting the depth of the surface material. Another empirical method of analysis has been proposed (25) for interpreting such curves, a brief summary of which follows.

In Figure 8 the smooth rounded Gish-Rooney curve is shown as a dash-line curve determined by the plotted crosses. The same field data are shown below this curve in the form of a cumulative resistivity curve determined by the plotted circles. When the values of apparent resistivity are plotted as a cumulative curve, a straight line or a curved line of gentle curvature is usually obtained so long as the "effective" current flow remains within the surface layer. When the electrode spacing is expanded to include increasing amounts of the deeper lying rock formation the cumulative curve shows an increased curvature upward, reflecting the influence of the higher resistivity of the rock formation. It has been found that straight lines drawn through as many points as practicable on the cumulative curve and intersecting in the region of increased curvature will give a good approximation of the thickness of the surface material if the point of intersection of the straight lines is projected to the horizontal or dimensional axis. This is a purely empirical relation with no theoretical basis whatsoever. It has given rather close approximations of the depth of the surface layer in simple two-layer formations, however.

Referring to Figure 8, it will be seen that the relatively shallow depth of 14.0 ft to rock, as determined by the test pit, affects strongly the measured values of apparent resistivity beyond an electrode spacing of about 10 ft. For this reason the plotted values of cumulative resistivity continue to show a rather marked degree of curvature well beyond what might be termed the "critical point" in the curve. The trend of the Gish-Rooney curve is used to

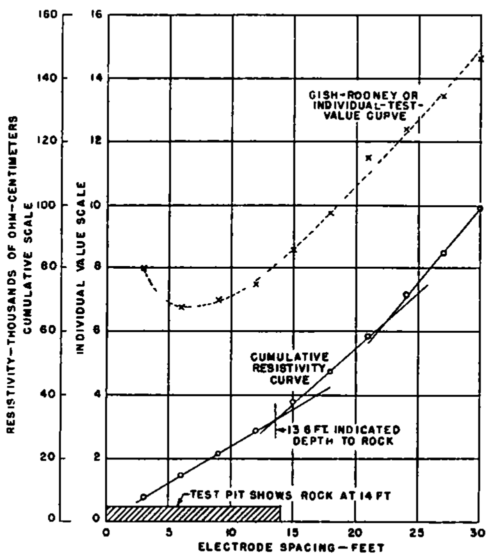


Figure 8. Typical Resistivity Data and Method of Analysis Using the Cumulative Resistivity Curve

determine the approximate "critical point" which in this curve appears to be at an electrode spacing of 10 to 12 ft. Guided by the indications of the Gish-Rooney curve and such other correlating data as may be available from test pits or borings in the general area, the additional tangent intersections beyond the "critical point" may or may not be disregarded.

Other methods of analysis of earth resistivity data based upon theoretical studies have been presented by Tagg (7), Hummel (4), Roman (6, 22), Wetzel, and McMurry (20), and others. Sets of theoretical curves for various assumed resistivities and thicknesses of materials involved have been prepared for use by the operator as control for interpreting the field curves obtained. In some instances the field data are plotted to the same scale as that used in the theoretical curves and on identical sheets and are superimposed upon the theoretical curves and where a "fit" is obtained the depths of the layers involved as well as the resistivities of each layer are obtained. Attempts to use these methods in analyzing the data obtained in the rel-

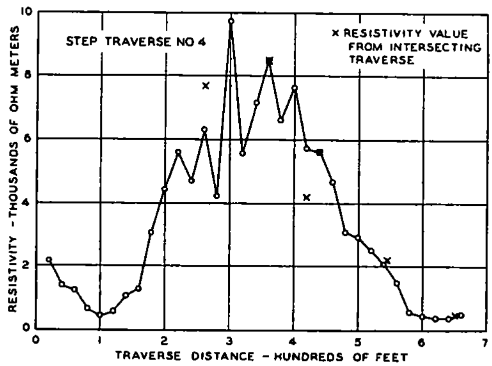


Figure 9. Step Traverse Over Deposit of Sandy Gravel - Electrode Spacing 20 Ft

atively shallow work done by the Bureau of Public Roads have been discouraging due to the time required for such studies and the frequency with which the field conditions failed to conform to those assumed in developing the theoretical curves. The empirical solutions heretofore described have been found to be more practical from the standpoint of time and cost in connection with a given exploration. This might be, in some cases, a deciding consideration between the geophysical tests and the direct methods of exploration ordinarily used.

When making surveys of areas a somewhat different test procedure, one which might be termed the "resistivity traverse" or "constant depth traverse", is often used. In this, a succession of tests using a fixed electrode spacing is made along the selected traverse line, the interval between test sites being equal to the electrode spacing. The measured resistivity values are then plotted as ordinates against traverse distance as abscissas and the resulting graph shows the variation in resistivity along the traverse line for a depth equal to the electrode spacing chosen. A typical example of such data is shown in Figure 9, the rise in resistivity between the 100-ft and 500-ft points on the traverse distance scale indicating the

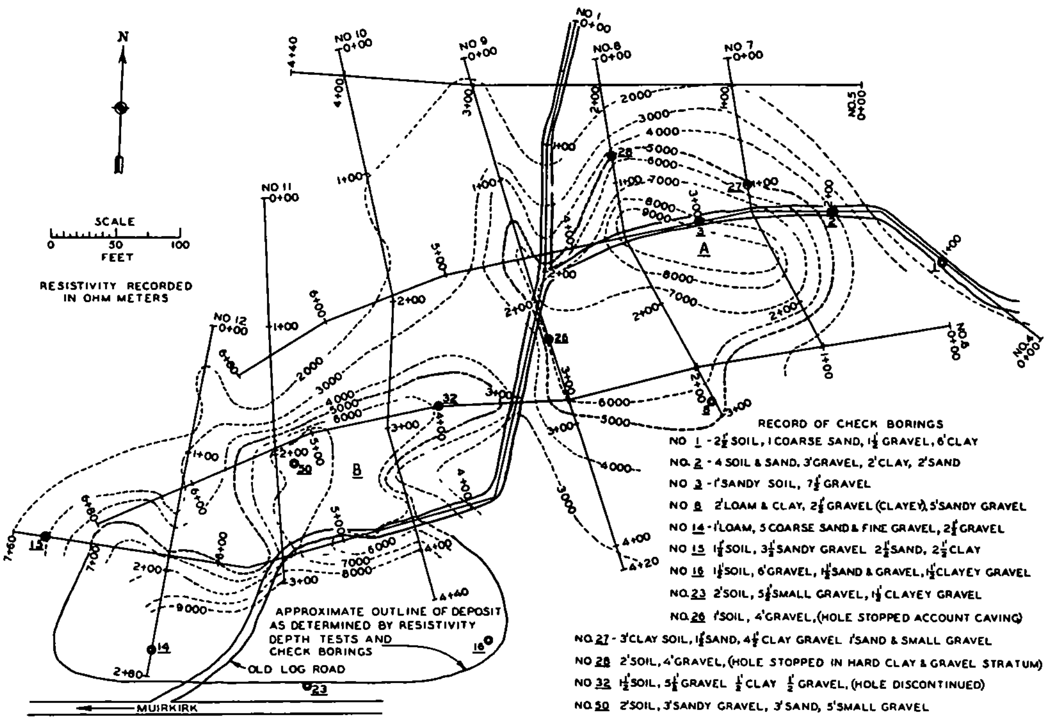


Figure 10. Resistivity Contour Map of a Deposit of Sandy Gravel

presence of higher resistance material within the depth explored. Traverse lines of this type carried out systematically over an area permit the preparation of a resistivity contour map, such as that shown in Figure 10. Such a map may be of considerable aid in rapidly locating and delineating critical areas that require more detailed study or that contain valuable isolated deposits of granular materials or rock in areas where such materials are scarce.

INCREASING NEED FOR RAPID AND INEXPENSIVE METHODS OF EXPLORING THE SUBSURFACE

Development during recent years of earth-moving equipment of ever increasing capacity has made possible the removal of huge quantities of excavation materials quickly and economically. However, operating costs of such equipment are high and a reasonably certain knowledge that the equipment selected will be able to handle all or a major portion of the materials on a given grading project, without costly delays from unforeseen adverse conditions, can be extremely helpful to contractors in establishing reasonable unit prices in bidding for the job. A thorough investigation of the subsurface formation prior to design of slopes in cut sections when preparing plans for a proposed roadway will help to avoid the confusion that results when solid rock cuts as shown on the plans actually are found to be soil or other easily removable materials. Such errors in the classification of materials may lead to increased costs and to the necessity for changes in design.

Stoney soil, talus materials and thin but continuous stringers of quartz or other hard materials extending throughout a cut may present insurmountable difficulties when attempting to explore subsurface conditions with hand or power operated auger equipment. Such troublesome conditions, although they may result in misleading data when the auger is used, will not affect the data obtained with geophysical tests to any appreciable extent. For this reason, preliminary surveys by geophysical methods can be used to considerable advantage in determining the overall character of the materials to be excavated and thus avoid errors of the type just mentioned. Complete and dependable information will make unnecessary hurried changes of alinement and grades to care for increased or decreased quantities of excavation materials, with possible delays of construction operations.

APPLICATION OF GEOPHYSICAL TESTS TO HIGHWAY CONSTRUCTION PROBLEMS DESCRIBED

It has been found that both seismic and resistivity methods of test are practical for use in the study of many highway construction problems. The earth resistivity apparatus, by reason of its simplicity of operation and the rapidity with which the shallow tests can be made is believed to have a more universal application than does the seismograph. Accordingly, when making a detailed geophysical survey of a grading project it has been the practice of the Bureau of Public Roads to make a resistivity survey first and, if necessary, to follow with a limited number of check tests with the seismograph in areas where the resistivity data have failed to adequately identify the subsurface formation. This procedure has been applied to 10 highway construction projects ranging from 1-1/2 to 12 mi. in length and located in the States of Virginia, North Carolina, Tennessee, Georgia, Arkansas, Missouri and in the District of Columbia. Reports have been received on four of these which have since been constructed and the conditions found during construction were substantially as predicted from results of the geophysical tests.

The following discussion will deal with the field data obtained with both types of apparatus. The discussion of the seismic method is rather brief in view of its somewhat limited use by the Bureau of Public Roads.

Results of Seismic Tests Described - In general, the velocity of the transmitted sound waves increases with an increase in the density of the transmission medium (soil, rock, etc.). Loose unconsolidated soil layers have wave velocities ranging from 600 to 1,500 ft per sec. More compact subsurface layers range from 2,000 to 9,000 ft per sec with the lower ranges 2,000 to 3,500 usually associated with clay materials and the higher ranges 4,000 to 9,000 with compact gravels, badly broken or weathered rock, and soil-boulder mixtures. Solid rock usually has wave transmission velocities between 10,000 and 20,000 ft per sec, depending upon the type of rock and its degree of weathering or fracture. In predicting the character of material that may be found, particularly in the intermediate velocity group (4,000 to 9,000 ft per sec), considerable judgment, as well as some knowledge of local geologic conditions, is required. Calibration tests over known subsurface formations are essential for a successful interpretation of the data obtained.

Actual identification of the materials involved is not always necessary, however. For example, broken rock or badly seamed rock, a highly compacted shale or a cemented gravel, having similar velocity characteristics, may also be expected to offer similar difficulties in excavation operations, possibly requiring some blasting and special handling and distribution. These same materials will probably show similar load carrying capacities when considered for foundation purposes, particularly where surrounded by materials which have been left in an undisturbed state. As an example, seismic tests made at Lincoln, New Hampshire, at a proposed bridge crossing of the Pemigewasset River, showed a comparatively high wave velocity for material lying only a few ft below the

Figure 11. View Showing Tightly Cemented Boulder Formation Predicted from Seismic Tests at Pemigewasset River Crossing Near Lincoln, New Hampshire

surface and apparently continuing to a depth of at least 40 ft. This material, with a wave velocity of 9,400 to 9,600 ft per sec, was predicted to be a tightly cemented boulder formation with excellent load carrying capacity. Figure 11 shows a view of subsequent excavation being made for one of the piers at this location. The material was so tightly cemented together that only a simple sandbag cofferdam was required. Soundings and drill holes through material of this type would be impossible or made only with great difficulty and at considerable cost.

Another bridge location, near Crater Lake, Oregon, was investigated by the seismic method in about 3 hr's time and the data obtained showed the subsurface formation to be a very dense material providing a wave velocity of 8,400 to 8,600 ft per sec. Here, again, there could be no doubt regarding the existence of adequate foundation materials. Figure 12 shows the seismic data for two of the three tests made at this location.

Experience is needed to determine the particular slope design that is adequate where certain materials within a local area are involved. With proper calibration data, the seismic method often can be relied upon to establish definitely the presence of the materials. As an example the data in Figure 13 show the presence and depth to the predominant material, shale.

As mentioned previously, portability

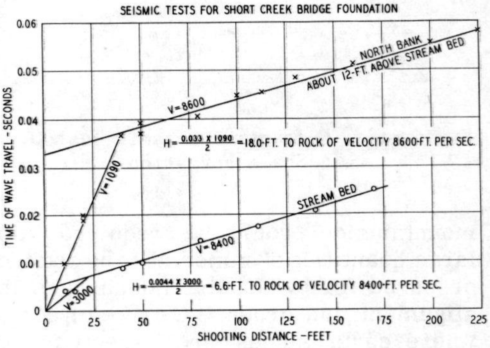


Figure 12. Time-Distance Graph Showing Results of Two Seismic Tests Made in Vicinity of Crater Lake, Oregon, While Investigating a Bridge Site on Short Creek

of equipment is of primary importance to the successful application of geophysical methods of test in preliminary surveys for a highway location. Figure 14 shows a view that is more or less typical of much of the terrain that is sometimes encountered in the construction of National Park and National Forest roads in various parts of the country. In designing for a modern highway through such country any information regarding the materials likely to be encountered in excavating cut sections is important. A close balance of quantities must be maintained in the interest of economy and of preserving the natural scenic beauty of the area. Unsightly borrow or waste areas are to be avoided. Therefore, a design prepared for solid rock with its 1/4 or 1/2 to 1 slopes in a cut section, such as the one shown in Figure 14, could lead to embarrassing difficulties should a comparatively loose earth or talus material be encountered. Should that happen a 1-1/4 or 1-1/2 to 1 slope reaching high up the

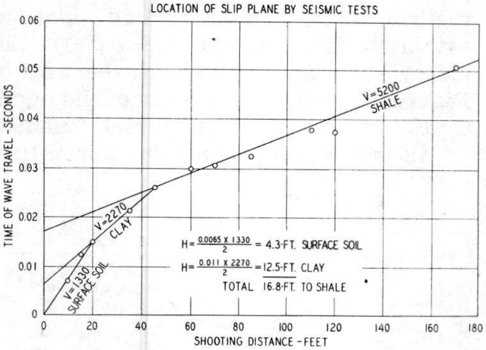


Figure 13. Refraction Seismic Test Over a Shale Formation

mountainside would be required with large quantities of material to be wasted or cared for by substantial changes in alignment and grade. Conversely, where earth slopes are expected and rock is found a source of borrow would be required for adjacent large fills unless major grade changes were made.

The ridge from which the photograph shown in Figure 14 was taken had been originally assumed to contain solid rock. A tunnel several hundred ft in length was proposed to carry the roadway through the ridge, some 100 ft below the top. Test pits dug to obtain design data for portal construction failed to encounter rock above grade. Several weeks were required for this exploration work which cost hundreds of dollars, and finally a redesign for an open cut was found necessary. Seismic tests requiring no more than two or three hr's time were sufficient to adequately establish the fact that no solid rock existed in the hill. The excavation during construction was made with the usual heavy earth-moving equipment. Studies made with seismic equipment at other sites have been of value in portal design and in indicating the probable need for lining in the tunnel.

Another problem to which refraction seismic equipment has been applied occurs in regions where slide conditions are prevalent. In some cases the loose talus material frequently involved in a slide rests upon a sloping shale forma-

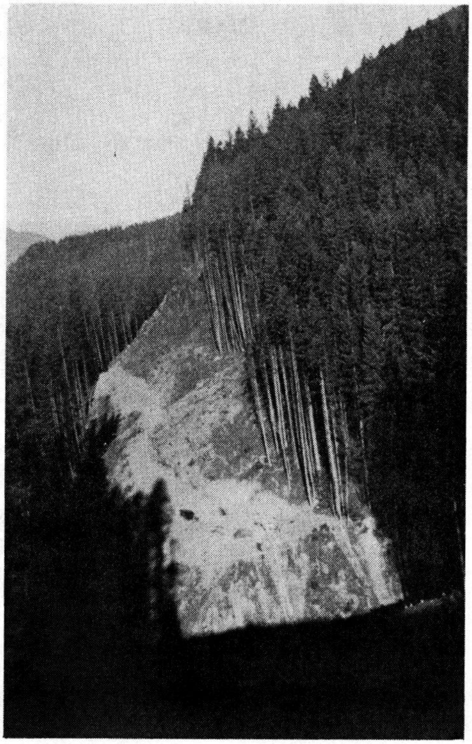


Figure 14. Rugged Construction Conditions for Highway Through National Forest Area in Oregon

tion which constitutes the sliding surface. This talus material has velocity characteristics differing from those of the more compact shales, making possible the location of the plane of separation.

Although the refraction seismic test has proved of value in preliminary surveys in various phases of highway construction, as has been pointed out, it has not been used to the same extent as the earth resistivity test in recent years because of the greater time required for a seismic test. Six or 8 seismic tests per 8-hr day is about the max number to be expected and under some field conditions even this number is not possible. Fifteen to 20 resistivity tests are usually possible under similar field conditions. Seismic tests can be utilized as a completely independent check of the indications of the more rapid resistivity tests, however, and are used for this important purpose in the routine work done by the Bureau of Public Roads.

in the Ozarks National Forest, in the course of a resistivity survey of about 22 mi. of proposed roadway. The calibration curves on the left were obtained for heavy sandstone ledges interbedded with shales and for the soils and decomposed shales typical of the

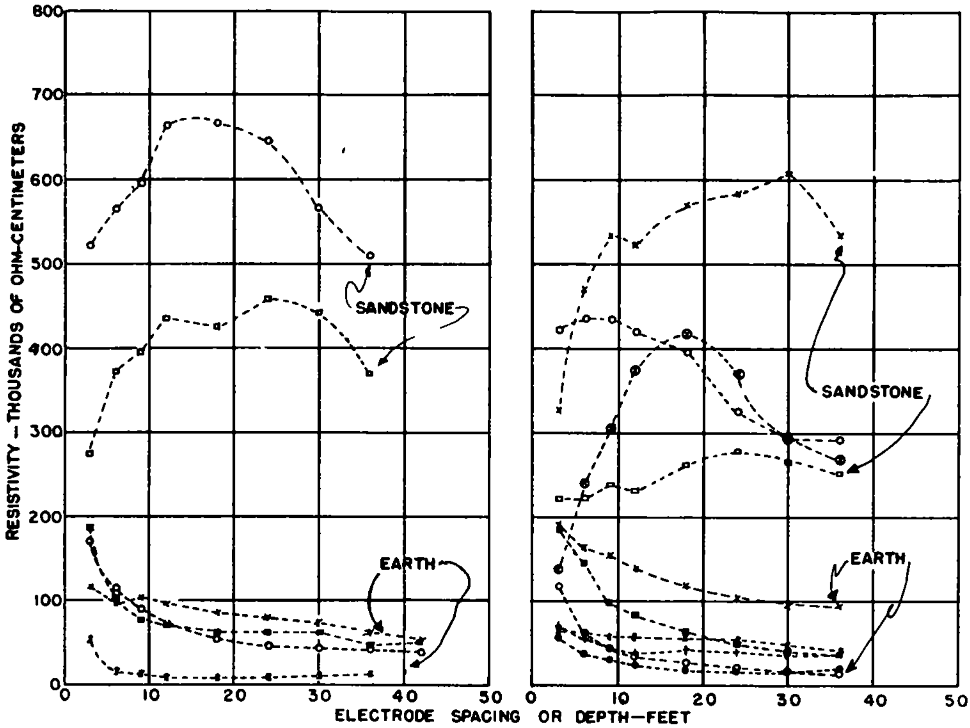


Figure 15. Resistivity Calibration Curves (Left) and Typical Field Curves Obtained in the Ozark National Forest Near Russellville, Arkansas

Earth Resistivity Tests Applied to Highway Grading Projects - In a subsurface survey in the field it is an established procedure to make calibration tests with the resistivity apparatus over exposures of formations believed to be typical of those in the area of immediate interest. Resistivity curves for the known conditions are then used for comparison with curves obtained over unknown conditions elsewhere in the area. From these comparisons reasonably accurate predictions can be made regarding the materials to be encountered below the surface and their location. Figure 15 shows typical resistivity curves obtained in Arkansas,

region. These latter are materials that could be handled with the heavy self-loading carryall scraper. Those curves of the right-hand graph are examples of the field curves obtained in the survey along the right-of-way of the proposed roadway. Little difficulty would be experienced in predicting the type of materials involved for the several curves shown. Figure 16 shows views of the two general types of material over which calibration tests were made.

Based upon the usual methods of direct exploration, the original slope design called for rock slopes over a considerable portion of the right-of-way. Actually, earth conditions, as predicted from the results of the resistivity survey, were found in a majority of the cuts during the construction of about 14 mi of roadway thus far completed.

The entire 22 mi was investigated in about 12 working days, one 8-mi project being covered in 3-1/2 days.

In northwest Georgia, resistivity calibration tests over solid rock and over earth formations produced curves as shown in the left and in the lower right-hand graphs, respectively, of Figure 17. Here again, although the shapes obtained are quite different from those obtained for materials of the same general classification in Arkansas, the two materials, rock and earth, can very easily be distinguished one from the other. On the basis of these calibration data, the typical field curves shown in the upper right-hand corner were all interpreted as "earth" curves representing materials easily removed by self-loading "pans". Figure 18 shows the two types of material over which calibrations were made.

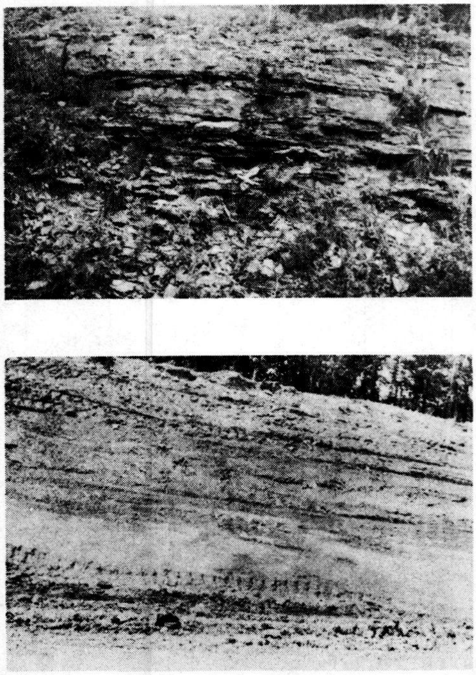


Figure 16. Views of Locations Where Resistivity Calibration Tests Were Made Over Rock (Upper) and Earth in Arkansas

In the Great Smoky Mountains National Park in western North Carolina, the dense granite rock formations typical of that area weather into a highly micaceous decomposed rock material that can be removed with self-loading "pans". As shown by the calibration curves presented in Figure 19 (solid line curves), this material has an extremely high resistivity, 1,500,000 ohm-cms, which is 10 times as great as resistivities found in some solid rock in other parts of the country. Due to the fact that the parent rock in a solid unweathered state has even higher resistivities (4,000,000 to 5,000,000 ohm-cms), it is again possible to differentiate between "earth" and rock excavation. The appearance of the materials over which the calibrations were obtained is shown in Figure 20. That section of the Blue Ridge Parkway on which the resistivity survey was made has not yet been built and no confirming correlations are available at the present time.

In southeast Missouri, the porphyry rock found in the vicinity of Farmington has a resistivity as indicated by the upper curve of Figure 21, while a calibration test over the soil common in the same area produced the lower curve of the figure, indicating almost no resistance to direct current flow. No difficulty was encountered in determining the type of material present in all but one cut of all those investigated on a 4-mi project.

Other resistivity surveys on construction projects in Tennessee, Virginia, Maryland, and in the District of Columbia have developed information regarding the subsurface formations that has been found to agree closely with conditions as actually found during construction.

Resistivity Tests Applied to Foundation Problems - Earth resistivity tests can be of assistance also in a subsurface study of the foundation conditions existing at proposed building sites, bridge locations, and in other areas where solid rock foundations are required or desirable.

In 1942, at the request of the Navy Department, a resistivity survey was made of a 150-acre tract at Carderock, Maryland, where a model testing basin is situated. The site is underlain with rock and information was desired as to axis, showed a difference in total amount of stripping of less than 6 percent from that computed from the rock contour map prepared in 1942. About 100,000 cu yd of stripping were involved.

Figure 23 shows typical traverse data obtained in this study and it illus-

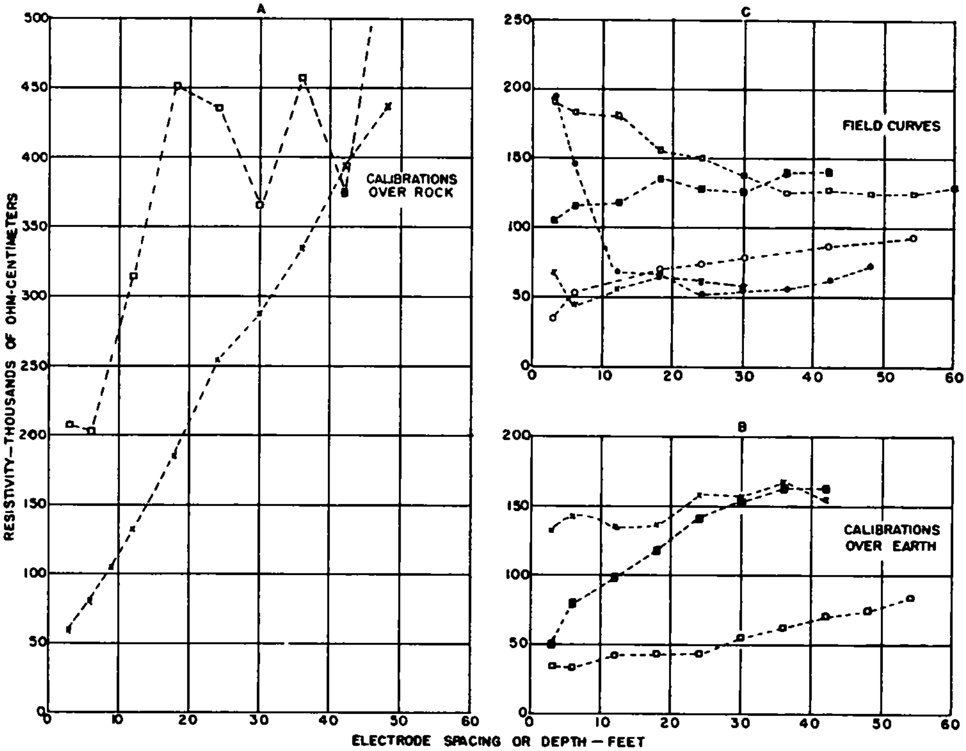


Figure 17. Resistivity Calibration Curves Obtained Over Earth and Rock Formations in Northwest Georgia and Typical Field Curves Obtained on Proposed Road Project North of Marietta

the depth to rock throughout the reservation. Altogether, over 500 depth tests and upwards of 10-1/2 mi of constant-depth resistivity traverse were made in carrying out the survey. From the information obtained a rock contour map, shown in Figure 22, was drawn up showing rock elevations on 2-ft contours over the entire area. An accuracy of ± 2 ft at any point in the area mapped was predicted. In 1944 an existing building with a width of 120 ft was extended for 1,800 ft in the area that had been mapped. Cross sections of the rock surface as found, obtained at intervals of 10 ft, along the building

trates how the resistivity test can be used in a preliminary survey to obtain information that may be used to guide a detailed survey by borings and eliminate many unnecessary soundings or borings. The flat-lying portion of the curve suggests a uniform condition for much of the distance traversed. The peaks in resistivity indicate those areas where direct borings should be concentrated to delineate in detail the obvious anomaly. These buried ridges of rock can be traced across wide areas, indicating regions where excavation will be difficult or where foundation conditions will be excellent at shallow depth. The figures shown underlined are depths to solid rock obtained by resistivity depth tests made at 100-ft intervals along the line of the traverse. The two depth curves shown in the inset are a striking indication of radical changes in the subsurface at stations 2+00 and 13+00 of the traverse.

In bridge foundation studies there have been numerous instances when the routine subsurface survey using the usual methods of probing, wash boring, etc., has failed to disclose unusual conditions later found during construction. Piers designed originally for solid rock foundations have had to be carried to considerably greater depths than those shown on the original plans, or supported upon piling extending to rock at a lower elevation. Figure 24 shows several resistivity depth curves obtained in a post-construction survey of a bridge crossing of the Flint River in southwest Georgia. The individual graphs show the plan data for depth of rock, the depth to rock as found during construction, and the depth to rock as predicted from the resistivity data. The general agreement between the results of the resistivity tests and the actual conditions existing is apparent.

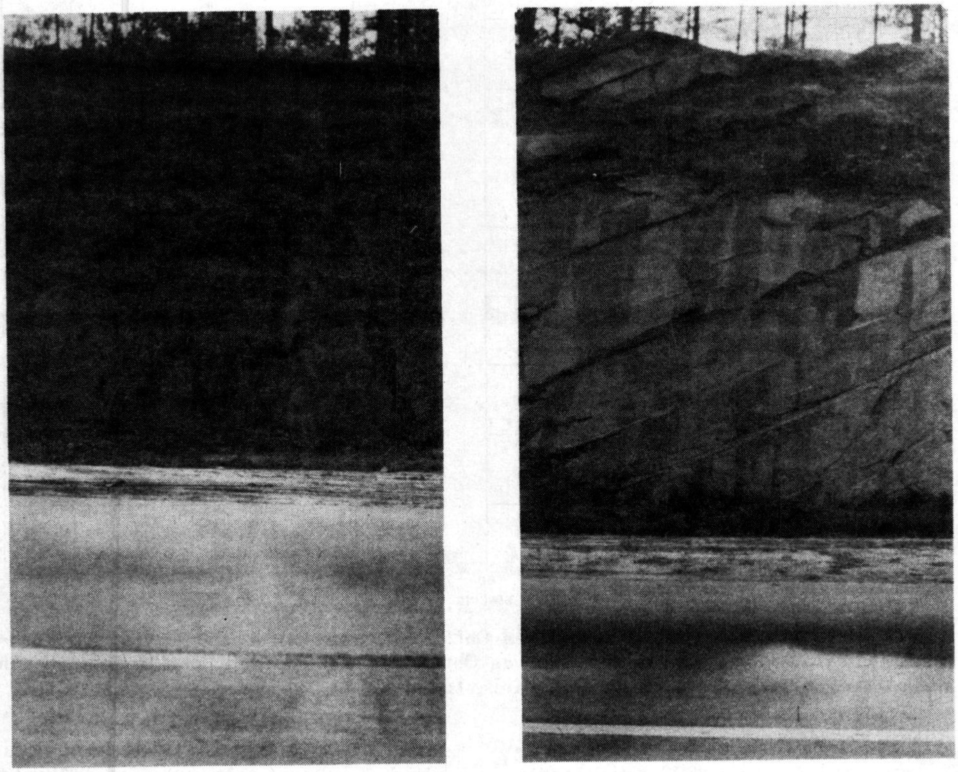


Figure 18. Locations of Resistivity Calibration Tests Made Over Earth and Solid Rock Formations in Georgia

Although it is not possible to make an unqualified statement regarding the effectiveness of the resistivity test generally in all localities and under all possible combinations of geologic formations, the fact remains that one or two hr's work at a particular location will usually determine the extent of its usefulness in solving the particular problem at hand. The data from the tests made in Georgia are similar to those that have been obtained elsewhere

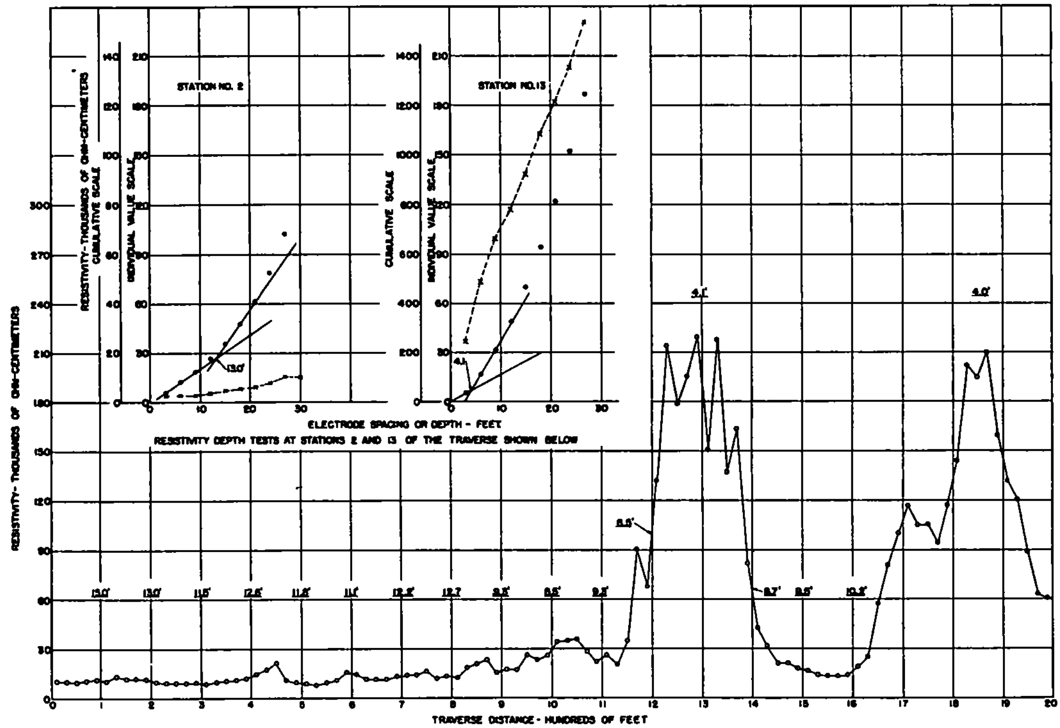


Figure 23. Earth Resistivity Constant - Depth Traverse Discloses Abrupt Changes in Rock Surface Underlying a Clay-Soil Overburden Traverse Involved a 20-ft Depth Along a 2000-ft Line - Figures shown underlined are results of resistivity depth tests for depth of overburden. Curves for two such tests are shown in inset.

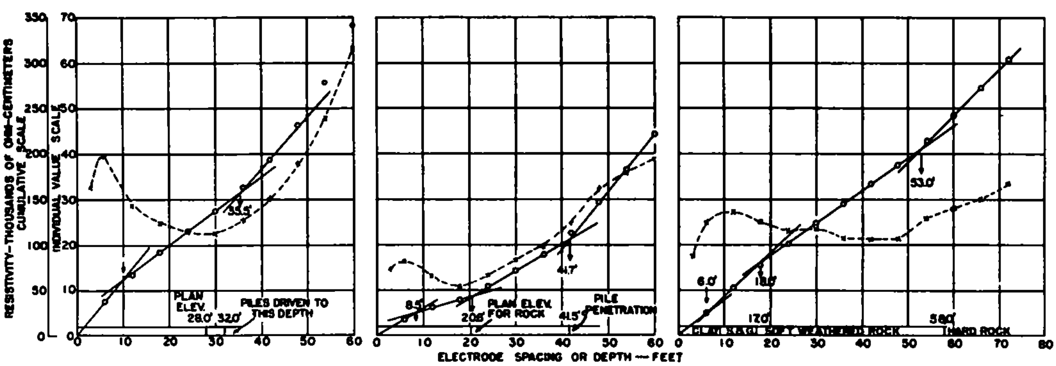


Figure 24. Earth resistivity tests at Flint River Crossing on US 19 south of Thomaston, Georgia, locate subsurface rock for bridge foundation more accurately than drill.

to the determination of conditions at a single designated spot or limited area such as a dam site, bridge location, etc. Even in the limited areas, if sharp irregularities of the rock surface present unfavorable conditions for consistent interpretation of the seismic data (24). To the writer's knowledge,

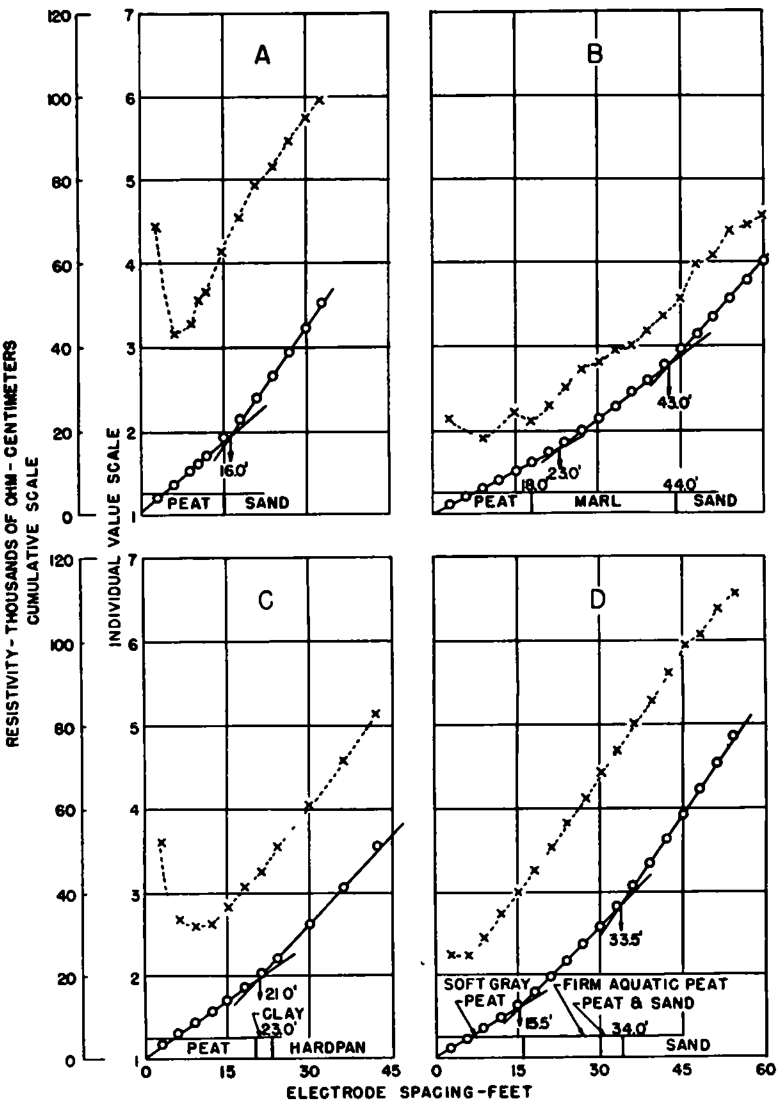


Figure 25. Resistivity Depth Tests Over Peat Bog Formations

differential weathering has been in progress, leaving pinnacles and deep valleys in otherwise hard rock, a condition sometimes encountered in limestone formations, the resistivity test may possibly prove the more valuable of the two methods. In such cases the however, there has been no report on results of resistivity tests carried out in such areas.

The use of explosives as required in the seismic method is not desirable in thickly populated areas. Compliance with local regulations regarding possession and transportation of explosives, sometimes rather strictly enforced, can be troublesome and inconvenient, placing a further handicap upon seismic exploration.

As mentioned previously, the time required for conducting a seismic test can vary from one to two or three hr, depending upon local conditions, while resistivity tests can be made at a rate of three per hr to depths of 60 ft in rugged mountainous terrain. A seismic party may require one or more men than are necessary for the efficient operation of the resistivity apparatus, particularly in isolated areas where supplies of explosives and film developing equipment must be carried in by hand. However, stray currents leaving cross-county pipe lines or emanating from electric railway systems in urban areas, and buried utilities such as water and gas pipes can, at time, be troublesome when making a resistivity survey. These will not affect the efficient use of the seismograph.

CONCLUSION

In conclusion it can be stated that, despite limitations that have been enumerated and others which may arise in future exploration work, the geophysical methods of test under consideration have definitely established their value in connection with highway work, particularly for use in preliminary surveys. Their use by the Bureau of Public Roads and other Federal agencies has emphasized the usefulness of these relatively inexpensive methods of test in shallow subsurface exploration in obtaining information to be used as control for design purposes or as control for more detailed subsurface surveys by core drilling and other commonly used direct methods. The fundamental principles of the two methods differ so widely that where both methods give concordant data they may be accepted with considerable assurance. As a result, when they are used jointly on a given project, a limited amount of confirming data from the seismic test can serve as a valuable check on a considerable number of the more inexpensive resistivity tests, at times obviating the need for test pits or auger holes for locating and identifying subsurface formations. This does not imply that test pits or auger holes may not be

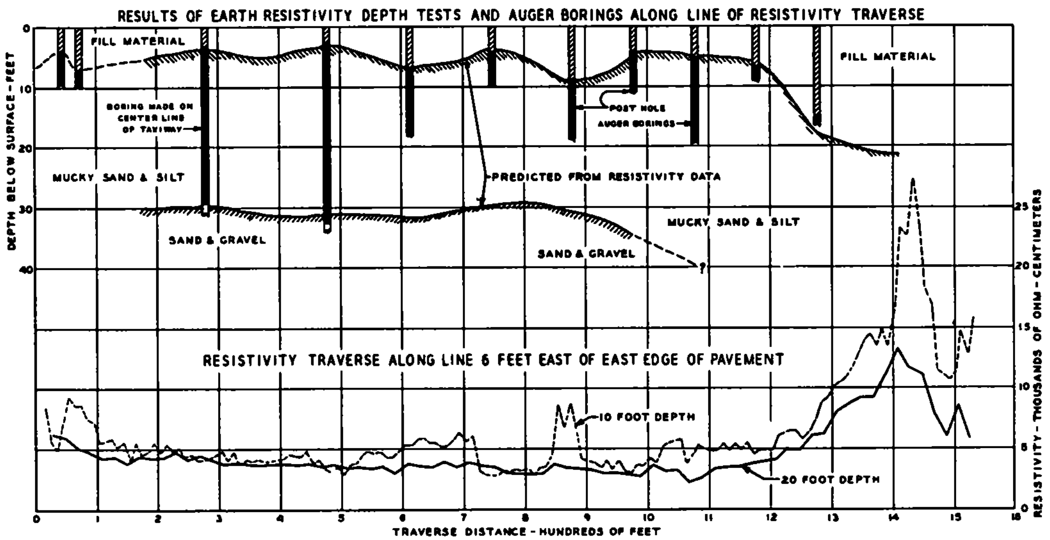
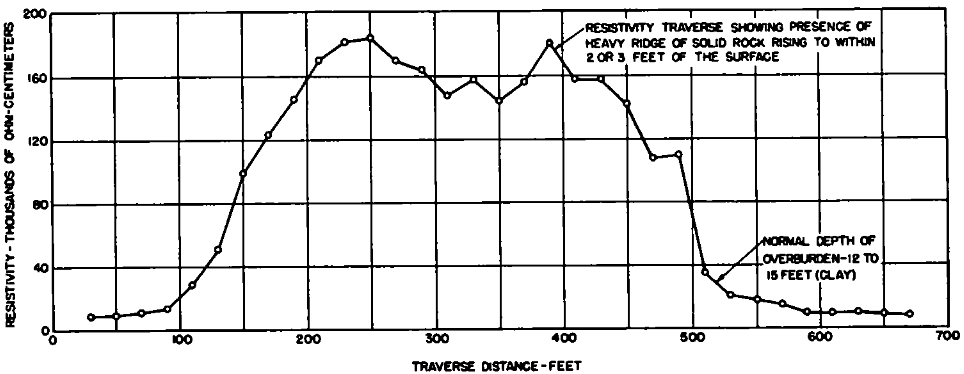
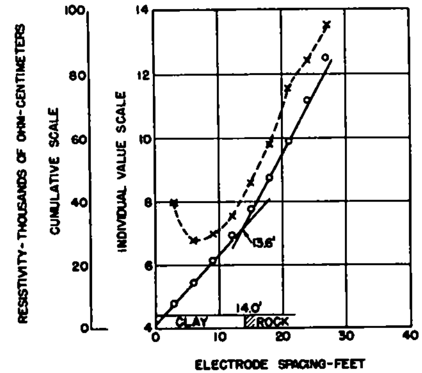


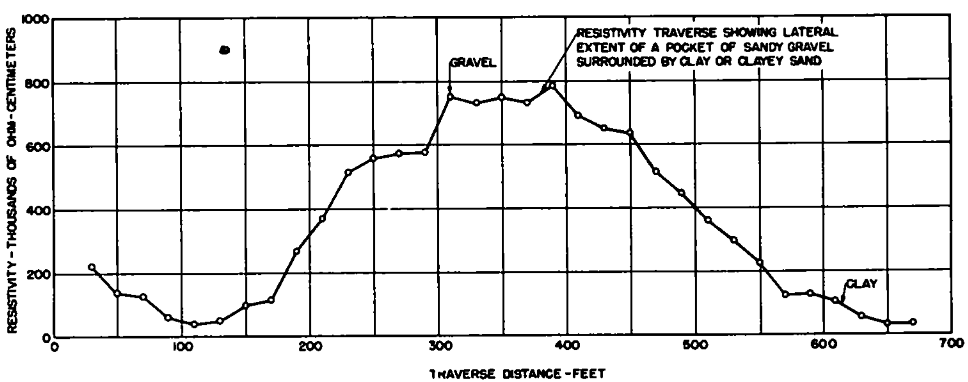
Figure 26. Results of Earth Resistivity Tests Along East Edge of Taxiway No. 4, National Airport, Washington, D. C. Traverse Station 0+00 = Station 11+17 Taxiway No. 4



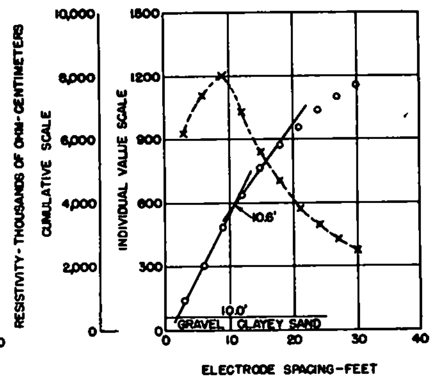
RESISTIVITY TRAVERSE OVER A BURIED GRANITE RIDGE USING A CONSTANT DEPTH OF 20 FEET



DEPTH TEST INVOLVING CLAY UNDERLAIN BY SOLID ROCK



RESISTIVITY TRAVERSE OVER A SAND AND GRAVEL DEPOSIT USING A CONSTANT DEPTH OF 20 FEET



DEPTH TEST INVOLVING SANDY GRAVEL UNDERLAIN BY CLAY OR CLAYEY SAND.

Figure 27.

necessary for obtaining samples of soil and other materials for determination of their physical and other properties.

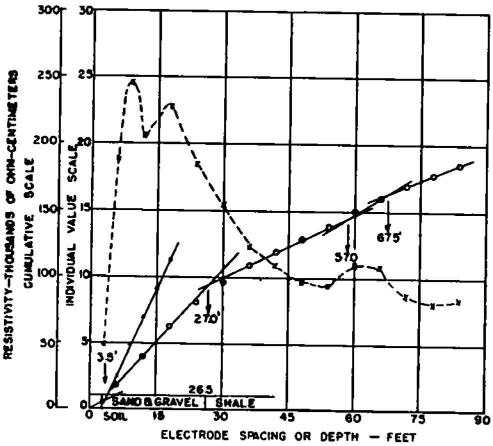


Figure 28. Resistivity Depth Test at Location of DH No. 2 19 in Right of Station 52 + 19, Susquehana River Crossing of the Pennsylvania Turnpike at Harrisburg

Even though there might exist some uncertainty that the geophysical methods of test would prove applicable to a particular subsurface condition, the simplicity, low cost and rapidity with which the tests can be made recommend their trial before resorting to the more costly and tedious methods of direct exploration ofttimes employed.

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GENERAL

1. Geophysical Abstracts, a bulletin published quarterly by the US Geological Survey, contains abstracts of currently published literature relative to subsurface exploration.

DISCUSSION

E. R. Shepard, Office of the Chief of Engineers - This paper is of particular interest to me, as we in the Corps of Engineers have been doing very similar work now for some 10 yr. The author has described very clearly the relative merits of the two methods of exploration and the particular types of problems to which each is most applicable.

Because of the relatively shallow depths with which highway construction is concerned, Mr. Moore has found the resistivity method generally preferable to the seismic method. Our explorations for the most part have been on dam sites and proposed canals, where the purpose of the test is to determine the depth to firm rock and here the seismic method has proved to be admirably suited. Best results are obtained in glaciated regions and in river flood plains where hard rock exists under alluvial or glacial deposits. Where the rock is shallow and the top deeply weathered or seamed and fractured, velocities are often no greater than those prevailing in some types of soil. Under these circumstances there is often a question as to the character of the material. Moisture is a major factor influencing velocity. In relatively dry overburden, velocities of about 1000 ft per sec or less are observed. With increasing moisture the velocity increases and in saturated sand and other coarse grained material attains a critical speed of 5000 ft per sec, or approximately that in water. In clays and other fine grained soils the critical velocity of 5000 ft per sec does not necessarily occur even though they may be fully saturated.

The fractured and seamed top zone of rock, particularly when dry and carrying only a thin overburden often exhibits a remarkably low velocity and for this reason may be mistaken for saturated sand or other unconsolidated material. A correct interpretation under such conditions may be highly important where excavation costs are concerned. Where the top of rock is at or near the water table, it is often difficult to determine whether the intermediate zone between low velocity top soil and hard, high velocity rock, is saturated sand or fractured rock. Where the top of rock is relatively deep, say 30 ft or more, the presence of moisture and the heavy load which closes up seams and fractures, tend to increase the velocity in the rock, leaving little question as to its presence and character. For these reasons better results are obtained by the seismic method at moderate and great depths than at shallow depths.

The cumulative method of interpreting resistivity data developed and used extensively by Mr. Moore appears to have been of great value in his exploration for highway construction and other shallow determinations. Seldom in nature do we find soils in layered formations to which theoretical formulae and curves are applicable. The man in the field is usually frustrated and discouraged in attempting to apply these principles to his data and is usually forced to fall back on some simple and rapid emperical method of analysis. The cumulative method, although not infallible, appears to give satisfactory results on the type of work described by the author and should receive the attention of other investigations engaged on similar projects.