Bridge Foundation Exploration by Electrical Resistivity Methods

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Geophysical methods of subsurface exploration afford a new tool to the engineer for use in connection with almost any of his problems involving an evaluation of underground conditions. These methods are not new, having been in use in the oil and mining industries for a number of years. However, their application to Civil Engineering problems is relatively recent, within the past 15 to 20 years, and they have found extensive use by engineers only since the war.

"Geophysical methods of exploration consist in identifying changes in the character of subsurface materials by measuring changes in certain physical characteristics of the earth at or near its surface." (1) Of the several methods available two have been found to be particularly adapted to the shallow work involved in engineering problems. These are the refraction seismic method in which the rate of propagation of elastic waves through the earth are measured, and the earth resistivity method which involves measurement of the electrical resistance of earth materials. Both methods have been used in bridge foundation explorations. The work here at Purdue has been limited to the electrical resistivity method, which is much the simpler and more economical of the two.

This work, which has been carried out by the Joint Highway Research Project for the past eight months, was initiated when the Indiana State Highway Department became interested in using the resistivity method for subsurface reconnaissance and general exploration work. A controlled research program was undertaken to establish the applicability of the method to specific conditions and problems in this region.

THEORY OF EARTH RESISTIVITY MEASUREMENTS

The electrical resistivity method of subsurface exploration consists of introducing a known current of electricity into the earth at the surface and measuring the resistance to flow for a given volume of earth. The resistivity of earth materials is dependent primarily upon the amount of ionized salts dissolved in the soil or rock moisture and therefore measurements of resistivity are only useful in so far as physical properties can be related to them. However it has been found that general groups of materials have characteristically different values of resistivity and that often general identification and more often changes in materials can be predicted from relative changes in resistivity.

The technique of measuring the resistivity of large masses of earth in place was first suggested in 1915 by Wenner (2). The method employs two current stakes and two potential electrodes in contact with the ground, with a means of inducing a known flow of current through the ground between the stakes and a method of measuring the potential drop between the two electrodes. The setup and necessary equipment are indicated in Figure 1. The equipment includes:

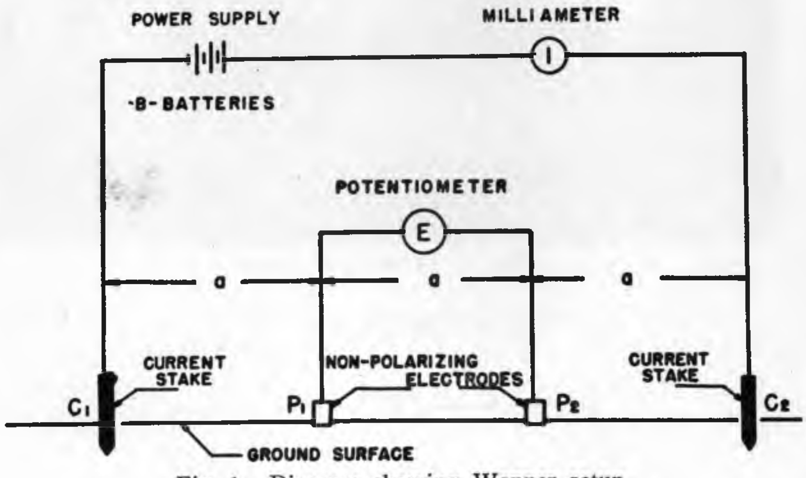

Fig. 1. Diagram showing Wenner setup.

1. power supply consisting of several 45 volt, radio-type, "B" batteries, 2. a milliameter to measure current flow, 3. a potentiometer to measure voltage drop, 4. copper coated steel current stakes, 5. porous pot non-polarizing electrodes, and 6. cable reels, leads, etc. The current flows in either direction between the two current stakes, the potential drop being measured between the two electrodes. The non-polarizing electrodes consist of a copper rod immersed in a solution of copper sulfate in a porous pot. The copper sulfate solution seeping through the porous pot makes contact with the ground. This arrangement is necessary to eliminate the effect of polarization potentials

at the contact between the electrodes and the ground. The one important feature to note in this diagram is that all contact points are collinear and equally spaced. This spacing which is known as the electrode interval will hereafter be referred to as the symbol "a".

Figure 2 shows a typical field set up at a small electrode interval. The middle potential electrode is for measurement by the Lee-Partitioning system which is a slight variation of the basic Wenner configuration.

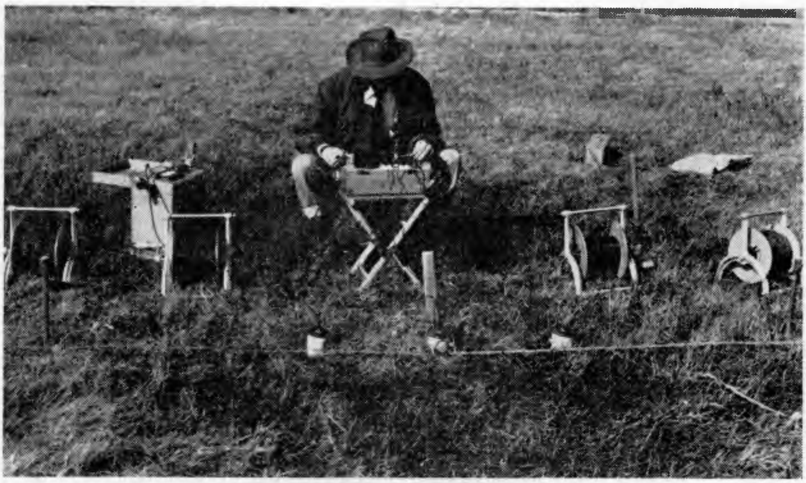

Fig. 2. Typical field setup.

Figure 3 is a schematic diagram indicating how the current flows through the earth. The current stakes are at the centers of the indi-

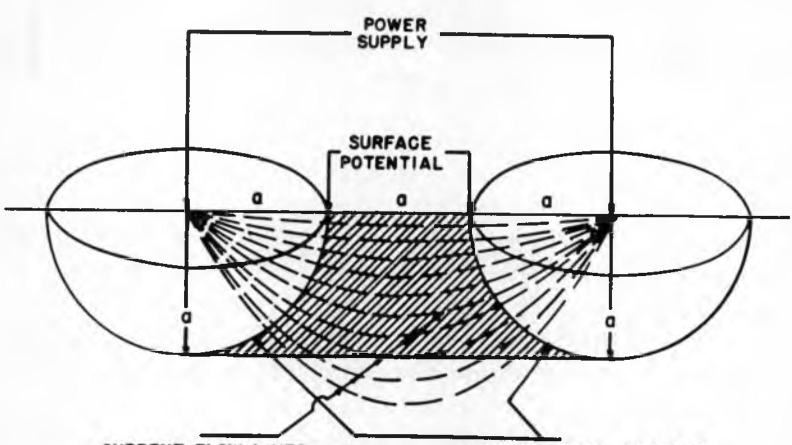

Fig. 3. Current flow diagram.

cated hemispheres with the potential electrodes at their inside edges. All contact points are collinear and equally spaced a distance "a". It can be shown that when the current source is a point on a plane that bounds a semi-infinite homogeneous medium, the equipotential surfaces are hemispheres with centers at the current source. Also, it has been proven experimentally that with the configuration shown the effective path of current flow is between the surface and a depth equal to "a". Thus if I, the amperage, and E, the voltage drop between the indicated equipotential surfaces are known, it can be shown that the resistivity of a volume of earth indicated by the shaded area is equal to $2\pi a \cdot E/I$. If a homogeneous material is being considered the specific resistivity of that material is measured. However earth materials are far from homogeneous. In these investigations the problem is simplified to a case of successive layers of different resistivity. The measured resistivity, therefore, is some weighted average of the various true resistivities of the soil strata and is known as the apparent resistivity.

VERTICAL PROFILES

A resistivity depth determination, commonly known as a vertical profile, consists of successive determinations of the apparent resistivity for increasing values of "a". The amount of increase in spacing between successive readings is the spacing increment which is generally kept constant for shallow profiles (less than 100 feet). In the work done here at Purdue an increment of 3 feet was almost always used resulting in an interval series of 3, 6, 9, 12, 15 feet, etc. Under favorable field conditions using a three-man party a vertical profile to a depth of 100 feet can be made in about an hours time. This is in contrast to an actual boring which would probably take one or more days.

The results of a resistivity depth determination are plotted as a curve of apparent resistivity versus electrode spacing. This is therefore a vertical profile of apparent resistivity. Figure 4 shows a vertical profile at the site of a bridge over the Wabash River at Peru, Indiana. It is from this curve that interpretations as to the nature and structure of the subsurface are made.

INTERPRETATION OF VERTICAL PROFILES

Up to this point the resistivity method is simple and direct. It has been stated (3) that "geophysical methods of measurement are direct, but their interpretation is always indirect. The problem is

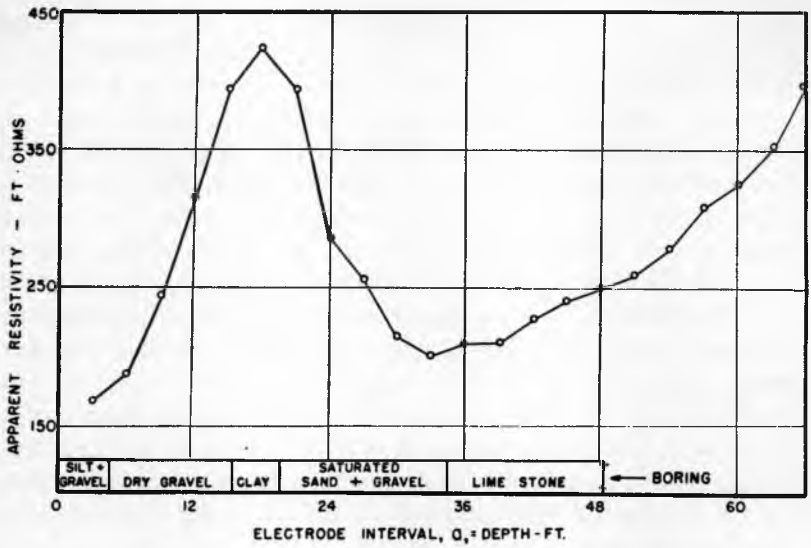

Fig. 4. Vertical profile No. 4, Wabash river at Peru, Indiana.

always one of deciding what geologic conditions and physical parameters could produce the measured results and, of all the possibilities, which is the most probable." For this reason the use of corroborating information such as well logs, borings within the general vicinity, resistivity curves over outcrops or exposures in road cuts, or geologic reports are very important to successful interpretation.

A rather large group of methods have been developed by geophysicists and engineers for the interpretation of resistivity curves. At least a dozen methods have been published. One of the main objectives of the work done here at Purdue was to determine which of these methods were most applicable to the specific conditions and problems encountered in Indiana. Eight methods were applied to each of the 46 field profiles made in this study (primarily at existing or proposed bridge sites in Indiana), and it was found that there were three that gave the most accurate and consistent results when the interpretations were compared with actual borings made at the site. The three that were used with the most success were the methods of Profile Breaks, Two-Layer Standard Curves, and Moore's Cumulative Curves.

Interpretation by means of profile breaks is a purely qualitative method, although one that is intuitionally applied to every resistivity curve regardless of what other more formal methods are also used. This method consists of predictions from the form of the basic resistivity curve, that is, observations of changes in apparent resistivity with increased electrode spacing. An understanding of the factors that effect resistivity is all that is needed to apply this method. The basic principle involved is that an increase of apparent resistivity with increased electrode spacing indicates a material of relative low resistivity overlying a material of higher resistivity, and conversely, a decrease of apparent resistivity with increased spacing indicates a material of relative high resistivity overlying one of lower resistivity. A study of the resistivity profile in Figure 4 will perhaps illustrate the basic principles of this method and of resistivity interpretation in general and will indicate how resistivity varies among general classes of materials.

This profile was made to a depth of 66 feet. The results of a boring made prior to the construction of the bridge at the same site as the electrical determination are shown at the top of the figure. It will be noted that the surface value of resistivity, at the 3 foot interval, in the dirty gravel is rather low, and that the curve slopes upward rather rapidly as the electrode interval equals the depth of the dry clean gravel. The slope starts to decrease when the clay layer is reached and reverses itself when this layer is more deeply penetrated, the values continuing to decrease through the layer of saturated sand and gravel. When the electrode interval equals the depth of the limestone bedrock the slope again becomes positive continuing through the end of the profile.

Most of the basic types of materials found in Indiana are represented in this profile. Our findings which agreed with work done by others showed that in unconsolidated materials the resistivity is lowest for wet clays and highest for dry sands and gravels, with intermediate types falling in between these. In other words, there is a general correlation between resistivity and moisture content, the resistivity varying inversely with the amount of water in the soil. Values for sedimentary rocks fall in the same range as those for soil, low for shales, higher for sandstones and limestones. The resistivity of igneous and metamorphic rock is very high making them readily identifiable.

The resistivity profile in Figure 4 should not be considered to be typical of Indiana conditions. It was selected as a simple illustration of the basic principles of resistivity interpretation. Interpretation was simple and direct in this case due to the fact that adjacent layers had strongly contrasting high and low values of resistivity.

Figure 5 shows a curve typical of another type in which there are no peaks or troughs or sharp breaks. Interpretation is less simple

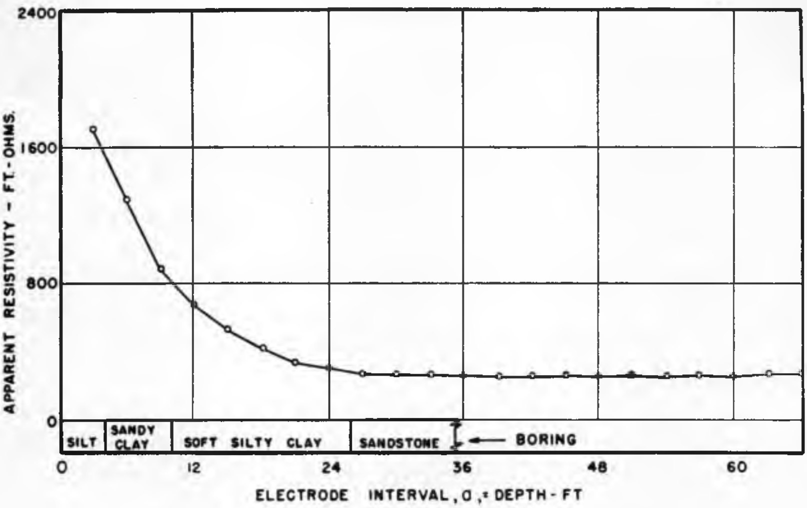

Fig. 5. Vertical profile No. 32, Jackson, Ohio.

in this case but none the less possible. An accurate interpretation was made for this curve through combined use of the three methods mentioned with particular emphasis in this case to matching with the Standard Two-Layer Curves which are theoretical curves derived mathematically.

Space does not permit a detailed consideration of this method.

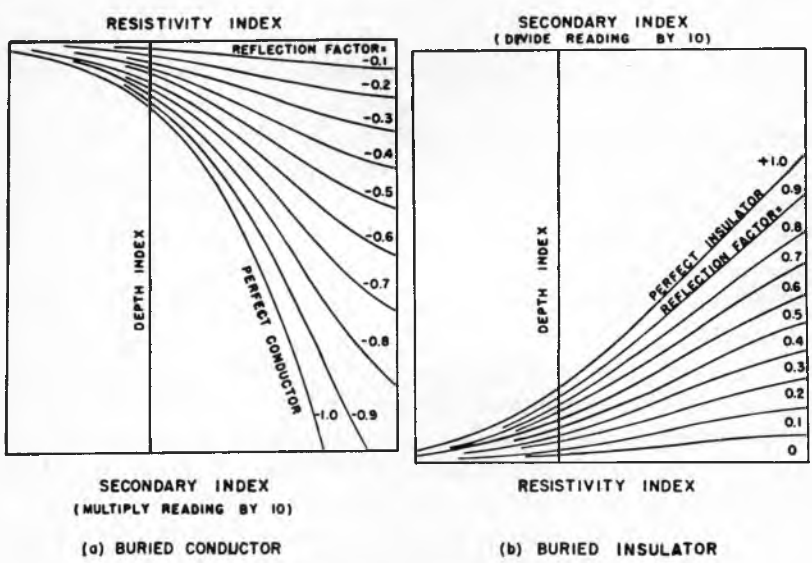

Fig. 6. Two-layer standard curves. (From Roman, 39).

Briefly, the method, which was developed by Roman (4), consists in matching the field curve plotted on a logarithmic scale to two families of standard curves, plotted to the same scale for the case of a single overburden overlying a basement material of infinite depth. The two families of a 2-layer standard curves are shown in Figure 6. The field curve is superimposed on the standard curves. If a match is found, then from this theoretical curve the depth of the layer interface and the resistivity of the two layers can be determined. While the method is directly applicable only to the two-layer case, it has been applied by means of successive determinations to three and more layers. In all the actual cases tested in this study more than two layers were represented.

Figure 7 shows the logarithmic plot of the profile given in Figure 5 with the various applicable two-layer standard curves superimposed. The sequence of the interpretation was as follows:

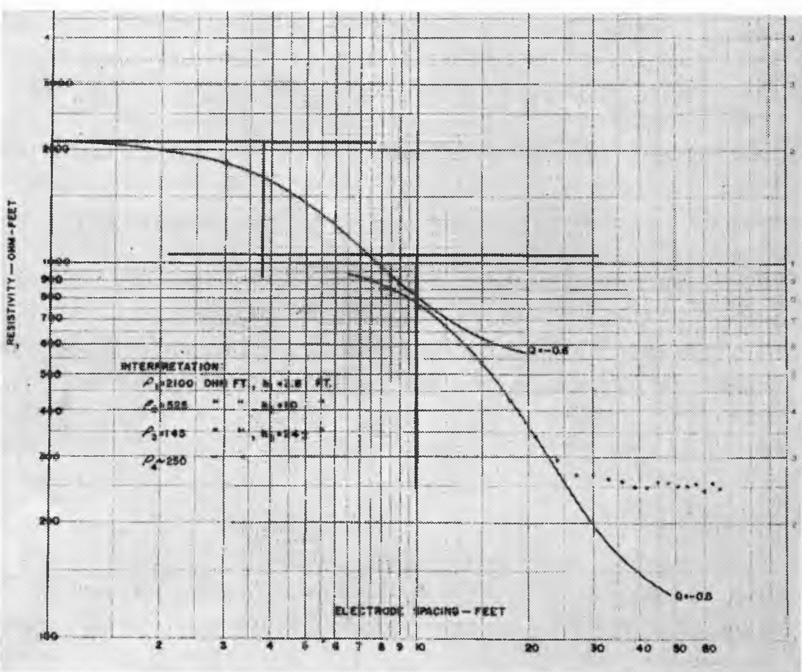

Fig. 7. Profile No. 32, interpretation by two-layer standard curves.

1. The first part of the data was matched with the -0.6 curves (-0.6 identifying the curve, – indicating a negative slope while 0.6 is Q, the reflection factor, $= p_2 - p_1 / p_2 + p_1$).

From this curve: $p_1 = 2100$ ohm – ft.
$h_1 = 3.8$ ft.

$$p_2 = 2100 \frac{(1-0.6)}{(1+0.6)} = 525 \text{ ohm-ft.}$$

The points deviate from the curve at around 12 feet, indicating a change in material near this depth.

2. The next few points were matched with the -0.8 curve. From this curve: $h_2 = 10$ ft.

$$p_3 = 1050 \frac{(1-0.8)}{(1+0.8)} = 115 \text{ ohm-ft.}$$

3. The points deviate from the curve at around 24 feet, indicating a change in material near this depth. There is no indication of further stratification with $p_4 = 250$ ohm–ft.
These values of p, especially p_2 and p_3, should be considered only as rough approximations. The important point is their relative values; that is $p_1 > p_2 > p_3$ and $p_4 > p_3$.

The third method which was applied with some success was Moore's Cumulative Method (5). Here interpretations are made from the cumulative curve which is actually the integral of the basic resistivity curve. The curve is plotted using for each ordinate the sum of the resistivities to that point, selected for equally spaced abscissas. Moore found, by testing many curves, that the slope of the cumulative curve changes near the separation that is numerically equal to the depth of a disturbing contact. Tangents are drawn near such slope changes and the abscissa at the intersection of these tangents is interpreted as being equal to the depth of the bed. The cumulative curve for the profile given in Figure 5 is shown in Figure 8.

Five other methods of interpretation were applied to all or most of the profiles studied in this research, none of which were found to be generally applicable to the conditions and problems here encountered. The five methods applied were Three-Layer Standard Curves, Longacre's Method, Rosenzweig's Method, Weighted Cumulative Curve, and Differential Curve. Discussions of each can be found in references (6, 7, 8, 3 and 5), respectively.

Table I gives the results of the evaluation of each of the eight methods as to their dependability in indicating layers and their

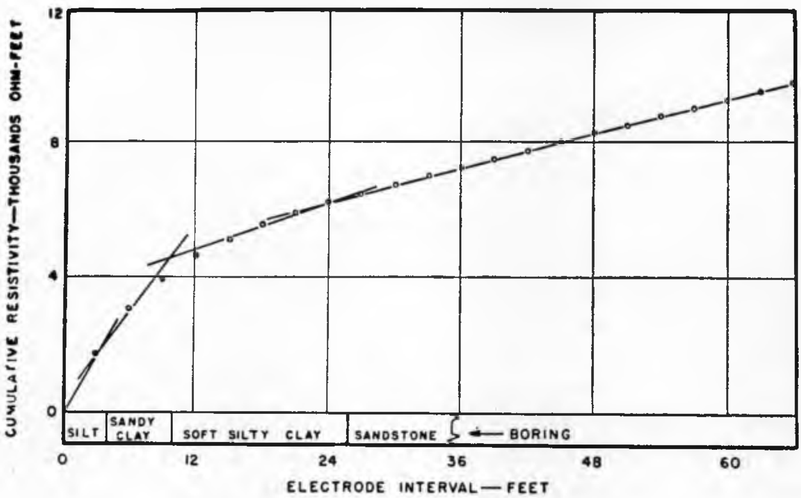

Fig. 8. Profile No. 32, cumulative curve.

accuracy in determining depths for the specific conditions encountered in this survey. Following is a brief explanation of the various ratings:

Good—The presence of each major layer was apparent, and the interpreted depths agreed within 3 feet of the actual.

Fair —All the major layers were indicated but with some disagreement in depths or there was no or only a slight indication of one of the boundaries.

Poor —General poor correlation or no indication at all of one or more layers.

None—No interpretation whatsoever due to inapplicability of method.

TABLE I
Summary of Results of Evaluation of Interpretation Methods

Interpretation Method	*No. of Applications*	*Good %*	*Fair %*	*Poor %*	*None %*
Profile Breaks	41	34	49	17	0
3-Layer	40	8	15	12	65
2-Layer	41	53	32	15	0
Longacre	23	22	9	22	47
Rosenzweig	39	5	8	21	66
Moore's	40	28	50	22	0
Weighted Cumulative	40	25	35	40	0
Differential Curve	40	22	23	55	0

From the results of this evaluation it was concluded that the methods of Profile Breaks, Two-Layer Standard Curves and Moore's Cumulative Curve were more applicable to Indiana conditions and problems.

RESULTS AND CONCLUSIONS

Although by use of the methods described above the various layers and their boundaries in a given profile can in most cases be determined rather accurately, it is still not always possible to predict what these layers represent. For instance it was generally not possible to predict the depth of bedrock at bridge sites, which were on alluvial deposits, from resistivity data alone due to the fact that the alluvial material was highly stratified and the resistivity of the typical overlying granular material was only slightly different from that of the underlying sedimentary rock. However, with the simplest of control data, for instance a geologic report of the general makeup of the area, it was found that accurate and dependable interpretations can be made probably 90 per cent of the time. In residual soil areas, where a relatively shallow simple overburden exists on bedrock, it has been found that interpretation is generally simple and accurate.

In conclusion, as a result of about eight months experience here at Purdue with the earth resistivity method of soil exploration we feel that it has definite application to all types of foundation exploration problems in this region. Our findings indicate that the method is particularly adapted to extending known information; that is, it is best used in connection with more definite methods such as borings. For example, if one or two borings are available in the general area of a proposed bridge, using the borings as control, 6 to 12 accurate and complete determinations can be made in a days time by electrical methods. Or to reverse the situation, approximate interpretations can be made from resistivity profiles in order to more intelligently plan the boring program. Finally, it has been shown that appreciable savings in time and money can be had through the use of resistivity methods in exploration programs.

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