Designation: D6431 – 99 (Reapproved 2010)

Standard Guide for Using the Direct Current Resistivity Method for Subsurface Investigation[1]

This standard is issued under the fixed designation D6431; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 *Purpose and Application:*

1.1.1 This guide summarizes the equipment, field procedures, and interpretation methods for the assessment of the electrical properties of subsurface materials and their pore fluids, using the direct current (DC) resistivity method. Measurements of the electrical properties of subsurface materials are made from the land surface and yield an apparent resistivity. These data can then be interpreted to yield an estimate of the depth, thickness, and resistivity of subsurface layer(s).

1.1.2 Resistivity measurements as described in this guide are applied in geological, geotechnical, environmental, and hydrologic investigations. The resistivity method is used to map geologic features such as lithology, structure, fractures, and stratigraphy; hydrologic features such as depth to water table, depth to aquitard, and groundwater salinity; and to delineate groundwater contaminants. General references are, Keller and Frischknecht (**1**),[2] Zohdy et al (**2**), Koefoed (**3**), EPA(**4**), Ward (**5**), Griffiths and King (**6**), and Telford et al (**7**).

1.2 *Limitations:*

1.2.1 This guide provides an overview of the Direct Current Resistivity Method. It does not address in detail the theory, field procedures, or interpretation of the data. Numerous references are included for that purpose and are considered an essential part of this guide. It is recommended that the user of the resistivity method be familiar with the references cited in the text and with the Guide D420, Practice D5088, Practice D5608, Guide D5730, Test Method G57, D6429, and D6235.

1.2.2 This guide is limited to the commonly used approach for resistivity measurements using sounding and profiling techniques with the Schlumberger, Wenner, or dipole-dipole arrays and modifications to those arrays. It does not cover the use of a wide range of specialized arrays. It also does not include the use of spontaneous potential (SP) measurements, induced polarization (IP) measurements, or complex resistivity methods.

1.2.3 The resistivity method has been adapted for a number of special uses, on land, within a borehole, or on water. Discussions of these adaptations of resistivity measurements are not included in this guide.

1.2.4 The approaches suggested in this guide for the resistivity method are the most commonly used, widely accepted and proven; however, other approaches or modifications to the resistivity method that are technically sound may be substituted if technically justified and documented.

1.2.5 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgements. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

---

[1] This guide is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.01 on Surface and Subsurface Characterization.

Current edition approved May 1, 2010. Published September 2010. Originally approved in 1999. Last previous edition approved in 2005 as D6431–99(2005). DOI: 10.1520/D6431-99R10.

[2] The boldface numbers in parentheses refer to the list of references at the end of this standard.

Copyright © ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959. United States

1.3 *Precautions:*

1.3.1 *It is the responsibility of the user of this guide to follow any precautions in the equipment manufacturer's recommendations and to consider the safety implications when high voltages and currents are used.*

1.3.2 *If this guide is used at sites with hazardous materials, operations, or equipment, it is the responsibility of the user of this guide to establish appropriate safety and health practices and to determine the applicability of regulations prior to use.*

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D420 Guide to Site Characterization for Engineering Design and Construction Purposes (Withdrawn 2011)[4]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D5088 Practice for Decontamination of Field Equipment Used at Waste Sites

D5608 Practices for Decontamination of Field Equipment Used at Low Level Radioactive Waste Sites

D5730 Guide for Site Characterization for Environmental Purposes With Emphasis on Soil, Rock, the Vadose Zone and Groundwater (Withdrawn 2013)[4]

D5753 Guide for Planning and Conducting Borehole Geophysical Logging

D6235 Practice for Expedited Site Characterization of Vadose Zone and Groundwater Contamination at Hazardous Waste Contaminated Sites

D6429 Guide for Selecting Surface Geophysical Methods

G57 Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method

3. Terminology

3.1 *Definitions:*

3.1.1 Definitions shall be in accordance with the terms and symbols given in Terminology D653.

3.1.2 The majority of the technical terms used in this document are defined in Sheriff (1991).

3.1.3 *Additional Definitions:*

3.1.3.1 *apparent resistivity*—the resistivity of homogeneous, isotropic ground that would give the same voltage-current relationship as measured.

3.1.3.2 *conductivity*—The ability of a material to conduct an electrical current. In isotropic material, it is the reciprocal of resistivity. The units of conductivity are siemens per metre.

3.1.3.3 *resistance*—opposition to the flow of direct current. The unit of resistance is ohms.

3.1.3.4 *resistivity*—the property of a material that resists the flow of electrical current. The units of resistivity are ohmmetres or ohm-feet (1 Ωm = 3.28 Ω-ft).

4. Summary of Guide

4.1 *Summary*—The measurement of electrical resistivity requires that four electrodes be placed in contact with the surface materials (Fig. 1). The geometry and separation of the electrode array are selected on the basis of the application and required depth of investigation.

4.1.1 In an electrical resistivity survey, a direct current or a very low frequency alternating current is passed into the ground through a pair of current electrodes, and the resulting potential drop is measured across a pair of potential electrodes (Fig. 1). The resistance is then derived as the ratio of the voltage measured across the potential electrodes and the current electrodes. The apparent resistivity of subsurface materials is derived as the resistance multiplied by a geometric factor that is determined by the geometry and spacing of the electrode array.

4.1.2 The calculated apparent resistivity measurement represents a bulk average resistivity of the volume of earth determined by the geometry of the array and the resistivity of the subsurface material. This apparent resistivity is different from true resistivity unless the subsurface materials are electrically uniform. Representative resistivity values of layers are interpreted from apparent resistivity values obtained from a series of measurements made with variable electrode spacing. Increasing electrode spacing may permit distinction among layers that vary in electrical properties with depth.

4.1.3 Most resistivity surveys for geologic, engineering, hydrologic, and environmental applications are carried out to determine depths of specific layers or lateral changes in geologic conditions at depths of less than a hundred metres. However, with sufficient power and instrument sensitivity, resistivity measurements are made to depths of several hundred metres.

4.2 *Complementary Data*—Other complementary surface geophysical methods (D6429) or borehole geophysical methods (Guide D5753) and non-geophysical methods may be necessary to properly interpret subsurface conditions.

5. Significance and Use

5.1 *Concepts*—The resistivity technique is used to measure the resistivity of subsurface materials. Although the resistivity of materials can be a good indicator of the type of subsurface material present, it is not a unique indicator. While the resistivity method is used to measure the resistivity of earth materials, it is the interpreter who, based on knowledge of local geologic conditions and other data, must interpret resistivity data and arrive at a reasonable geologic and hydrologic interpretation.

5.2 *Parameter Being Measured and Representative Values:*

5.2.1 Table 1 shows some general trends for resistivity values. Fig. 2 shows ranges in resistivity values for subsurface materials.

5.2.2 Materials with either a low effective porosity or that lack conductive pore fluids have a relatively high resistivity

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] The last approved version of this historical standard is referenced on www.astm.org.

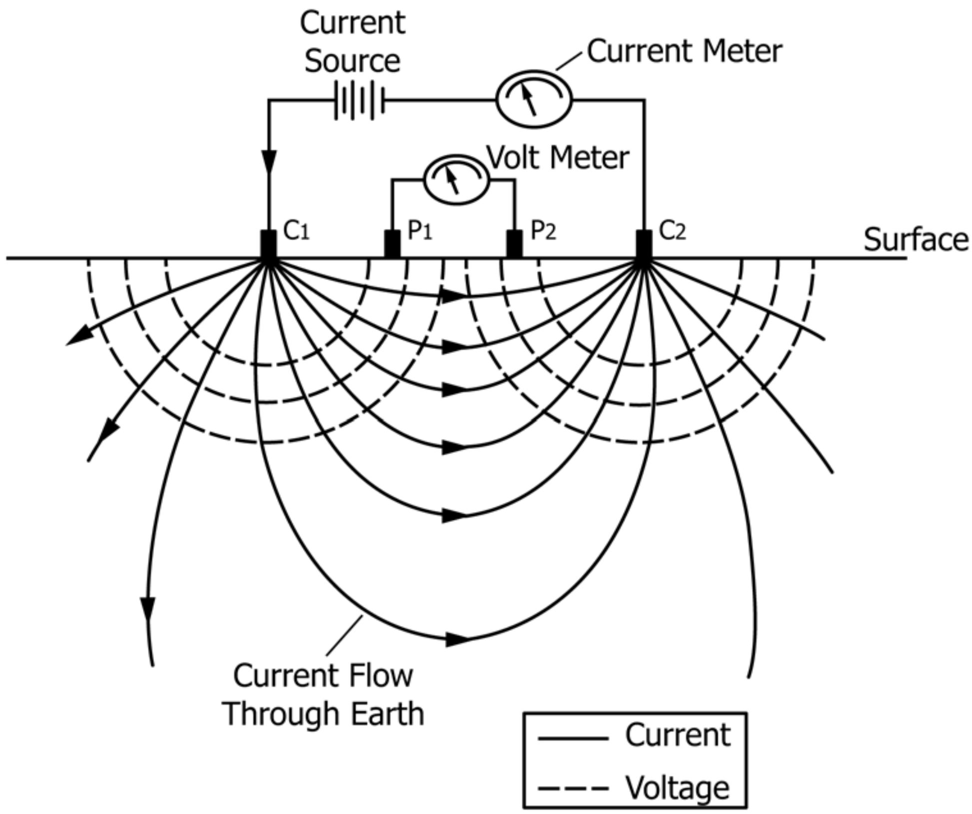

FIG. 1 Diagram Showing Basic Concept of Resistivity Measurement (from Benson et al, (8))

TABLE 1 Representative Resistivity Values for Soil, Water, and Rock (Mooney (4))

Regional Soil Resistivity	Ωm
- wet regions	50–200
- dry regions	100–500
- arid regions	200–1000 (sometimes as low as 50 if the soil is saline)
Waters	Ωm
- soil water	1 to 100
- rain water	30 to 1000
- sea water	order of 0.2
- ice	105 to 108
Rock Types	Ωm
- igneous and metamorphic	100 to 10,000
- consolidated sediments	10 to 100
- unconsolidated sediments	1 to 100

(>1000 Ωm). These materials include massive limestones, most unfractured igneous rocks, unsaturated unconsolidated materials, and ice.

5.2.3 Materials that have high porosity with conductive pore fluids or that consist of or contain clays usually have low resistivity. These include clay soil and weathered rock.

5.2.4 Materials whose pore water has low salinity have moderately high resistivity.

5.2.5 The dependence of resistivity on water saturation is not linear. Resistivity increases relatively little as saturation decreases from 100 % to 40-60 % and then increases much more as saturation continues to decrease. An empirical relationship known as Archie's Law describes the relationship between pore fluid resistivity, porosity, and bulk resistivity (McNeill (**10**)).

5.3 *Equipment*—Geophysical apparatus used for surface resistivity measurement includes a source of power, a means to measure the current, a high impedance voltmeter, electrodes to make contact with the ground, and the necessary cables to connect the electrodes to the power sources and the volt meter (Fig. 1).

5.3.1 While resistivity measurements can be made using common electronic instruments, it is recommended that commercial resistivity instruments specifically designed for the purpose be used for resistivity measurements in the field.

5.3.2 Commonly used equipment includes the following elements:

5.3.2.1 A source of current consisting of batteries or a generator,

5.3.2.2 A high-impedance voltmeter or resistivity unit,

5.3.2.3 Metal stakes for the current and potential electrodes, and

5.3.2.4 Insulated wire to connect together all of the preceding components.

5.3.3 Care must be taken to ensure good electrical contact of the electrodes with the ground. Electrodes should be driven into the ground until they are in firm contact. If connections between electrodes and the insulated wire are not waterproof, care must be taken to ensure that they will not be shorted out by moisture. Special waterproof cables and connectors are required for wet areas.

5.3.4 A large variety of resistivity systems are available from different manufacturers. Relatively inexpensive battery-powered units are available for shallow surveys. The current

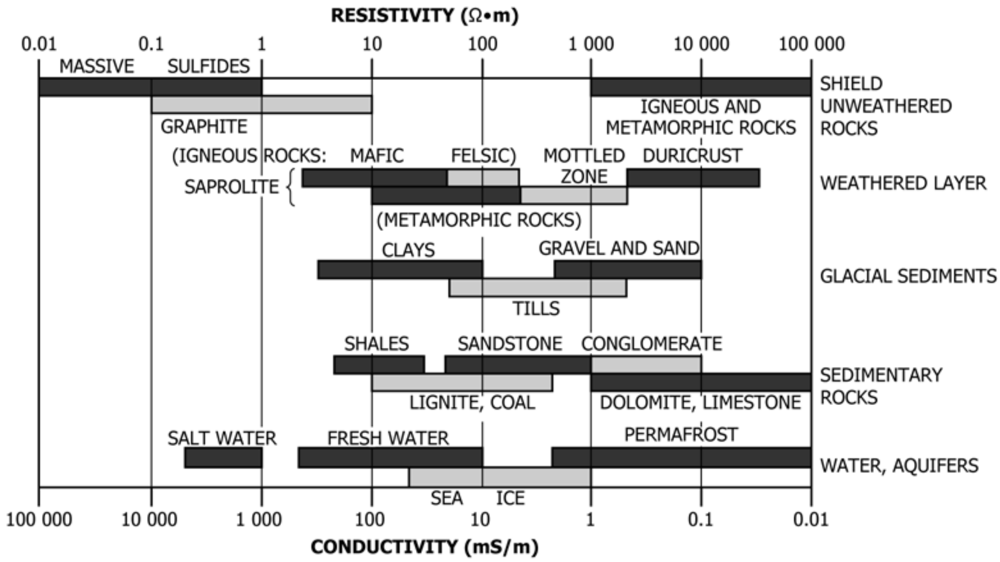

FIG. 2 Typical Ranges of Resistivities of Earth Materials (from Sheriff, (9))

source (transmitter) and the potential measurement instrument (receiver) are often assembled into a single, portable unit. In some cases, the transmitter and receiver units are separate. High power units capable of deep survey work are powered by generators. The current used in dc resistivity surveys varies from a few milliamps to several amps, depending on the depth of the investigation.

5.3.5 *Signal Enhancement*—Signal enhancement capability is available in many resistivity systems. It is a significant aid when working in noisy areas or with low power sources. Enhancement is accomplished by adding the results from a number of measurements at the same station. This process increases the signal-to-noise ratio.

5.4 *Limitations and Interferences :*

5.4.1 *Limitations Inherent to Geophysical Methods:*

5.4.1.1 A fundamental limitation of all geophysical methods lies in the fact that a given set of data cannot be associated with a unique set of subsurface conditions. In most situations, surface geophysical measurements alone cannot resolve all ambiguities, and some additional information, such as borehole data, is required. Because of this inherent limitation in geophysical methods, a resistivity survey alone is never considered a complete assessment of subsurface conditions. Properly integrated with other information, resistivity surveying is an effective method of obtaining subsurface information.

5.4.1.2 All surface geophysical methods are inherently limited by decreasing resolution with depth.

5.4.2 *Limitations Specific to the Resistivity Method:*

5.4.2.1 Interpretation methods assume horizontal (or parallel) layered conditions where each layer has a uniform electrical resistivity. If subsurface conditions cannot be reasonably approximated by this assumption, then results will be in error.

5.4.2.2 Thin layers or multiple layers with similar resistivities may not be detected.

5.4.2.3 Ambiguities in interpretation arising from equivalence (where two resistive layers carry nearly the same electric current if the products of their resistivity and thickness equal).

5.4.2.4 Ambiguities in interpretation arising from suppression (where resistant layers are sandwiched between more conductive layers).

5.4.2.5 Extremely resistive materials will prevent current injection into the ground.

5.4.3 *Interferences Caused by Ambient and Geologic Conditions:*

5.4.3.1 The resistivity method is sensitive to electrical interference from a variety of sources. It is inherently sensitive to electrical interference. Spatial variables caused by geologic factors and cultural factors may also produce noise.

5.4.3.2 *Ambient Sources of Noise*—Natural (ambient) sources of noise include lightning or natural earth currents, which may induce a voltage in resistivity cables.

5.4.3.3 *Geologic Sources of Noise*—Geologic sources of noise include local inhomogeneities near electrodes that may result in measurement error and variations in the subsurface that are not the object of the survey.

5.4.3.4 *Cultural Sources of Noise*—Resistivity measurements may be influenced by nearby cultural features (such as power lines, radio stations, cathodic pipeline protection, and other geophysical equipment) that generate electrical or electromagnetic fields. Pipelines, fences, and metal buildings may also affect them.

5.4.3.5 *Leakage*—A resistivity measurement may also be affected by leakage from the insulated wire used to connect the instrument to the electrodes. Tests for leakage can be made at the time of the measurement.

5.4.4 *Summary*—During the course of designing survey locations, potential cultural interferences should be considered. During the survey, the occurrence of electrical interferences should be noted.

5.5 *Alternate Methods*—The limitations previously discussed may prohibit the effective use of the resistivity method, and other methods may be required to resolve the problem. An alternative to the resistivity method is the EM method, which is preferred in high-resistivity (low-conductivity) materials, and may require less space to conduct the survey.

5.6 *Electrode Array Geometry*—Usually the electrodes are arranged in a collinear array in one of several fixed geometries. Several standard electrode geometries have been developed for various applications (Fig. 3). For engineering, environmental, and groundwater studies, the Wenner, Schlumberger, and dipole-dipole arrays are the most commonly used.

5.6.1 *Wenner Array*—The Wenner array consists of equally spaced, in-line electrodes (Fig. 3). The formula for calculating apparent resistivity from a Wenner measurement is:

$$R = 2\pi a(V/I) \quad (1)$$

where:

a = electrode spacing,
V = measured voltage, and
I = current.

5.6.2 *Schlumberger Array*—The Schlumberger array consists of unequally spaced in-line electrodes (Fig. 3), where $AB > 5\,MN$. The formula for calculating apparent resistivity from a Schlumberger measurement is:

$$R = \pi \frac{(AB/2)^2 - (MN/2)^2}{MN} \times \frac{V}{I} \quad (2)$$

where:

AB = distance between current electrodes, and
MN = distance between potential electrodes.

5.6.3 *Dipole-Dipole Array*—The dipole-dipole array consists of a pair of closely spaced current electrodes and a pair of closely spaced potential electrodes (Fig. 3). The formula for calculating apparent resistivity from a dipole-dipole measurement is:

$$R = \pi na\,(n+1)\,(n+2)\,(V/I) \quad (3)$$

where:

n = distance between innermost electrodes, and
a = distance between the current electrodes and also the potential electrodes.

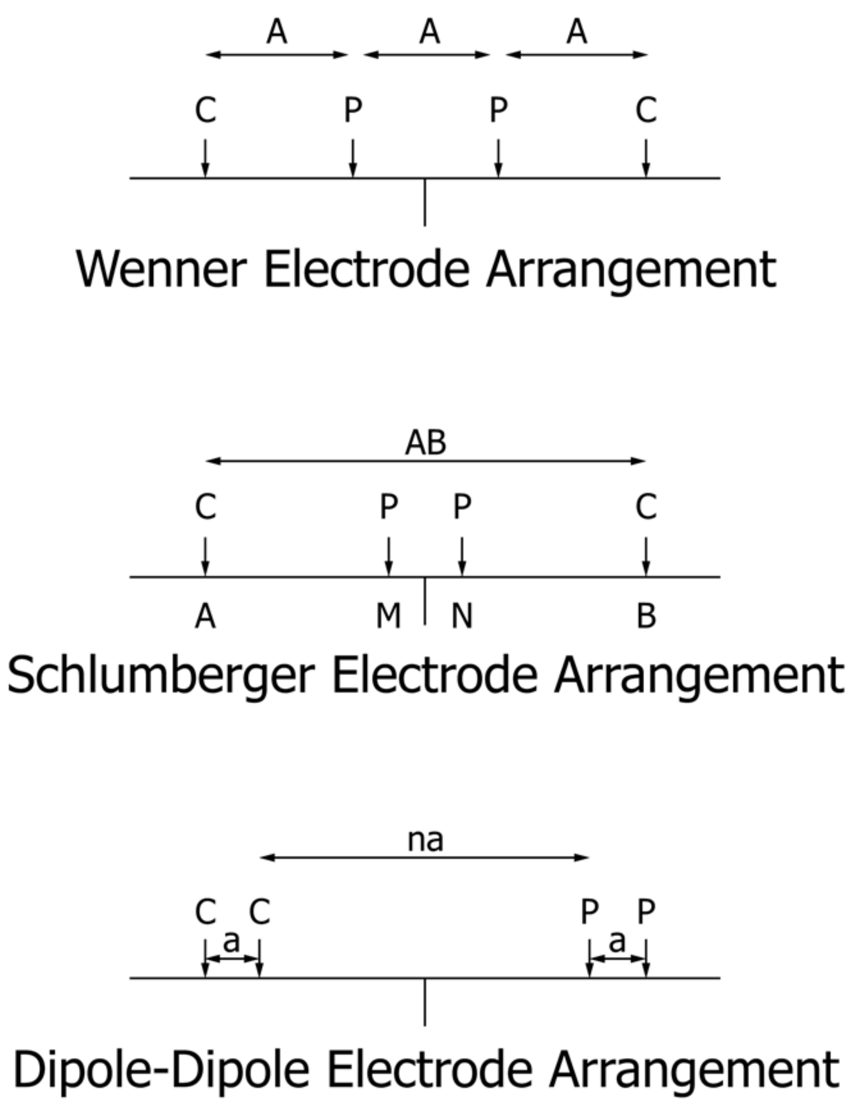

FIG. 3 Standard Electrode Geometries

5.6.4 *Comparison of the Arrays:*

5.6.4.1 *The advantages of Schlumberger arrays:*

(1) Schlumberger arrays are less susceptible to contact problems and the influence of nearby geologic conditions that may affect readings. The method provides a means to recognize the effects of lateral variations and to partially correct for them.

(2) Schlumberger arrays are slightly faster in field operations since only the current electrodes must be moved between readings.

5.6.4.2 *Advantages of Wenner Arrays:*

(1) The Wenner array provides a higher signal to noise ratio than other arrays because its potential electrodes are always farther apart and located between the current electrodes. As a result, the Wenner array measures a larger voltage for a given current than is measured with other arrays.

(2) This array is good in high-noise environments such as urban areas.

(3) This array requires less current for a given depth capability. This translates into less severe instrumentation requirements for a given depth capability.

5.6.4.3 *Advantages of Dipole-Dipole Arrays:*

(1) Relatively short cable lengths are required to explore large depths.

(2) Short cable lengths reduce current leakage.

(3) More detailed information on the direction of dip of electrical horizons is obtainable.

5.6.5 *Other Arrays*—There are several other arrays: Lee-partitioning array (Zohdy et al (**2**)), square array (Lane et al (**11**)), gradient array (Ward (**2**)) and pole-dipole (Ward (**5**)) and automated data acquisition and imaging systems that are not discussed in this guideline.

5.7 *Sounding (Depth) Measurements* —Sounding measurements are one of the most widespread uses for the resistivity technique. Soundings provide a means of measuring changes of electrical resistivity with depth at a single location. Several measurements are made with increasing electrode spacings. As the spacing of the electrodes is increased, there is an increase in the depth and volume of material measured (Fig. 4). The center point of the array remains fixed as the electrical spacing is increased.

5.7.1 This method can be used to determine changes in lithology, stratigraphy, and depth to water table. These depths are interpreted from measurements of apparent resistivity.

5.7.2 Sounding measurements result in a series of apparent electrical resistivity values at various electrode spacings. These apparent resistivity values are plotted against electrode spacing using a log-log scale (Fig. 5) and are interpreted using inversion techniques to derive true resistivity and thickness of subsurface layers.

5.7.3 Successive electrode spacings should be (approximately) equally spaced on a logarithmic scale. Normally, 3 to 6 data points per decade should be measured. A resistivity sounding curve obtained from measurements of a uniform layered medium should follow a smooth curve, (Fig. 5). By using six points per decade, noise is generally less significant and a smooth sounding curve may be obtained. Data should be plotted in the field to ensure that an adequate number of noise-free measurements are made.

5.7.4 The depth of penetration for an inhomogeneous stratified earth depends upon the electrode separation and the resistivities of the earth's layers. In general, the overall array length could be many times the exploration depth.

5.8 *Profiling Measurements*—A series of profile measurements along a line is used to assess lateral changes in subsurface conditions at a given depth (Fig. 6). Electrical resistivity profiling is accomplished by making measurements with fixed electrode spacing and array geometry at several stations along a profile line (Fig. 7). A single profile measurement results in an apparent electrical resistivity value at a station. Several profiles over an area can be used to produce a contour map of changes in subsurface conditions (Fig. 8). These apparent resistivity profiles or maps can not be interpreted in terms of layer resistivity values without sounding data or other additional information.

5.8.1 Vertical soundings are used to determine the appropriate electrode spacing for profiling. Small electrode spacings can be used to emphasize shallow variations in resistivity that may affect the interpretation of deeper data. Spacing between measurements controls the lateral resolution that can be obtained from a series of profile measurements.

6. Procedure

6.1 *Qualification of Personnel* —The success of a resistivity survey, as with most geophysical techniques, is dependent upon many factors. One of the most important is the competence of the persons responsible for planning, carrying out the survey, and interpreting the data. An understanding of the theory, field procedures, and methods for interpretation of the resistivity data along with an understanding of the site geology is necessary. Personnel not having specialized training or

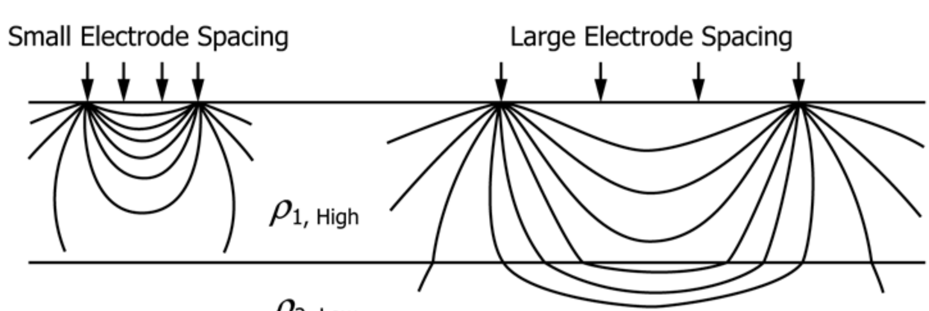

FIG. 4 Increased Electrode Spacing Samples Greater Depth and Volume of Earth (from Benson et al, (8))

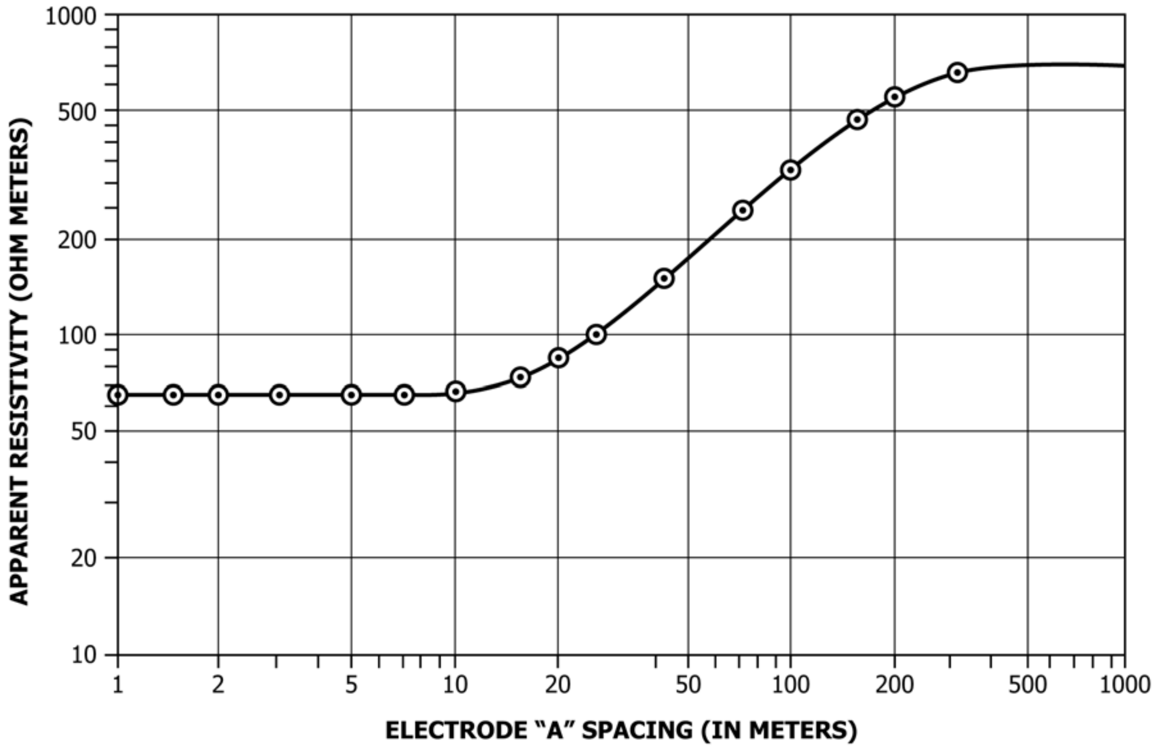

FIG. 5 Resistivity Sounding Curve (from Benson et al, (8))

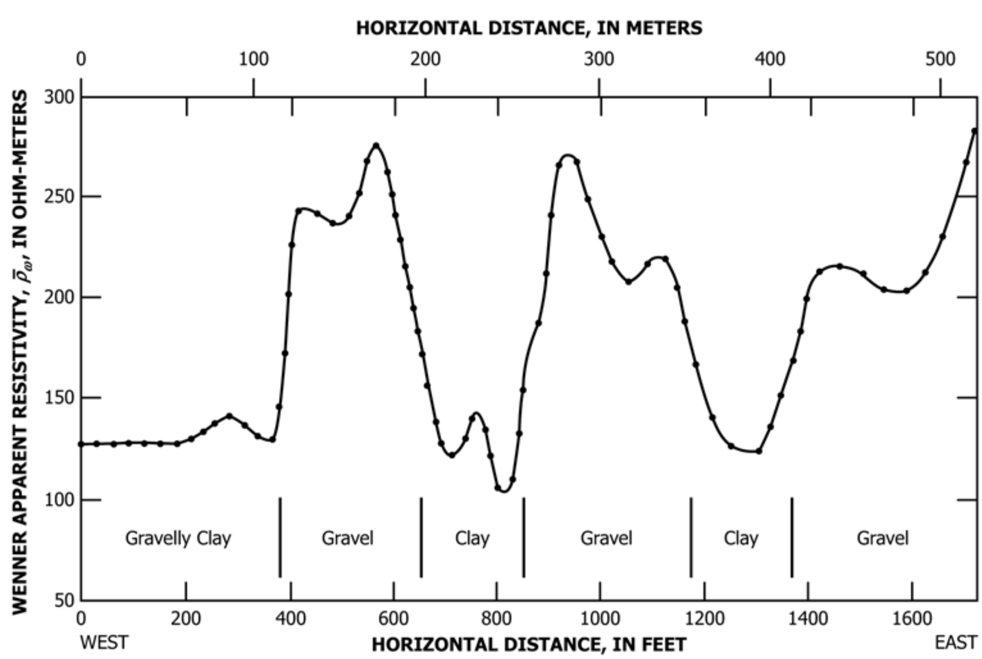

FIG. 6 Profiling to Assess Lateral Changes (from Zohdy et al, (12))

experience should be cautious about using this technique and solicit assistance from qualified practitioners.

6.2 *Planning the Survey*—Successful use of the resistivity method depends to a great extent on careful and detailed planning.

6.2.1 *Objectives of the Resistivity Survey:*

6.2.1.1 Planning and design of a resistivity survey should be done with due consideration to the objectives of the survey and the characteristics of the site. These factors will determine the survey design, the equipment used, the level of effort, the interpretation method selected, and the budget necessary to achieve the desired results. Important considerations include

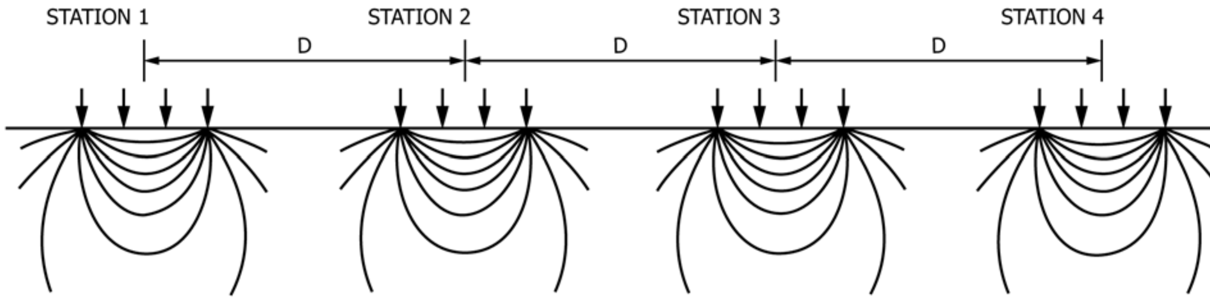

FIG. 7 Stations Along a Profile (from Benson et al, (8))

site geology, depth of investigation, topography, and access. The presence of noise-generating activities (on-site utilities, man-made structures) and operational constraints (impervious surfaces) must also be considered. It is good practice to obtain as much relevant information as possible about the site prior to designing a survey and mobilizing to the field.

6.2.1.2 A simple conceptual model of hydrogeologic conditions at the site should be developed early in the design phase and should include thickness and type of soil cover, depth and type of rock, depth to water table, and stratigraphy.

6.2.1.3 The intent of the survey may be for reconnaissance of subsurface conditions or to provide detailed subsurface information. In reconnaissance surveys, station spacing is large and topographic maps are usually sufficient for location. Under these conditions, the effort to obtain resistivity data is relatively low, but the resulting subsurface data are not detailed. In a detailed survey, station spacing is small and locations of measurements are more accurately determined using surveying methods or GPS techniques. Under these conditions, the effort to obtain resistivity data is greater but the data are more detailed.

6.2.2 *Assess Resistivity Contrast:*

6.2.2.1 One of the most critical elements in planning a resistivity survey is the determination of whether or not there is an adequate resistivity contrast between the two geologic or hydrologic units of interest.

6.2.2.2 In situations where no previous resistivity surveys have been made in the area, knowledge of the geology, published references containing the resistivity values of earth materials, and published reports of resistivity studies done in similar hydrogeologic settings are required. When there is doubt as to whether there is sufficient resistivity contrast, preliminary field work should be considered near a control point, such as a borehole or well, where the stratigraphy is known so that the resistivity values of sediments and rocks in the area can be determined and the feasibility of using the resistivity method assessed. A resistivity or induction (conductivity) log may be run in boreholes on or near the site to provide resistivity (conductivity) values with depth and aid in assessing the potential success of the surface resistivity method.

6.2.2.3 A forward model can be used to plot the apparent resistivity versus electrode spacing for an assumed thickness and resistivity of subsurface layers. These results are used to predict the success of the resistivity method in resolving the desired layer or layers and to help determine the geometry of the field-survey. However, all too often, sufficient information about layer thickness and resistivity will not be available to accurately model a site before fieldwork is carried out. Therefore, initial field measurements should be undertaken to address whether or not an adequate resistivity contrast exists between the subsurface layers of interest.

6.2.3 *Selection of the Approach:*

6.2.3.1 The desired level of detail and complexity of the site will determine the field procedures to be used.

6.2.3.2 The following should be considered:

(1) Whether sounding or profiling will be used,

(2) The type of array, and

(3) The type of equipment, selected based upon desired depth of investigation and type of array used.

6.2.4 *Planning the Survey Grid:*

6.2.4.1 *Location of Survey Lines*—Preliminary location of survey lines is usually done with the aid of topographic maps and aerial photos if an on-site visit is not possible. Consideration should be given to the following:

(1) The need for data at a given location,

(2) The accessibility of the area,

(3) The proximity of wells or test holes for control data,

(4) The extent, location, and impact of any surface features such as asphalt or concrete; buried structures and utilities; and other sources of cultural noise that can prevent measurements from being made or introduce noise into the data, and

(5) Adequate space for the resistivity line.

6.2.4.2 Errors in measurements and subsequent calculations can be minimized by the following considerations for the resistivity array and survey line layout:

(1) The array should lie along as straight a line as possible; deviations from a straight path may result in inaccuracies unless they are carefully surveyed and appropriate corrections are applied to the data.

(2) Often the location of the line is determined by topography. Line locations should be selected so that the ground surface along each array is as flat as possible unless the locations are carefully surveyed and appropriate corrections are applied to the data.

6.2.4.3 *Coverage*—Consideration should also be given to the lateral extent of the survey coverage, the orientation of the survey lines, and the detail required in mapping the features of interest. The area of the survey should usually be larger than the area of interest so that measurements are taken in both "background" conditions and over any anomalous conditions.

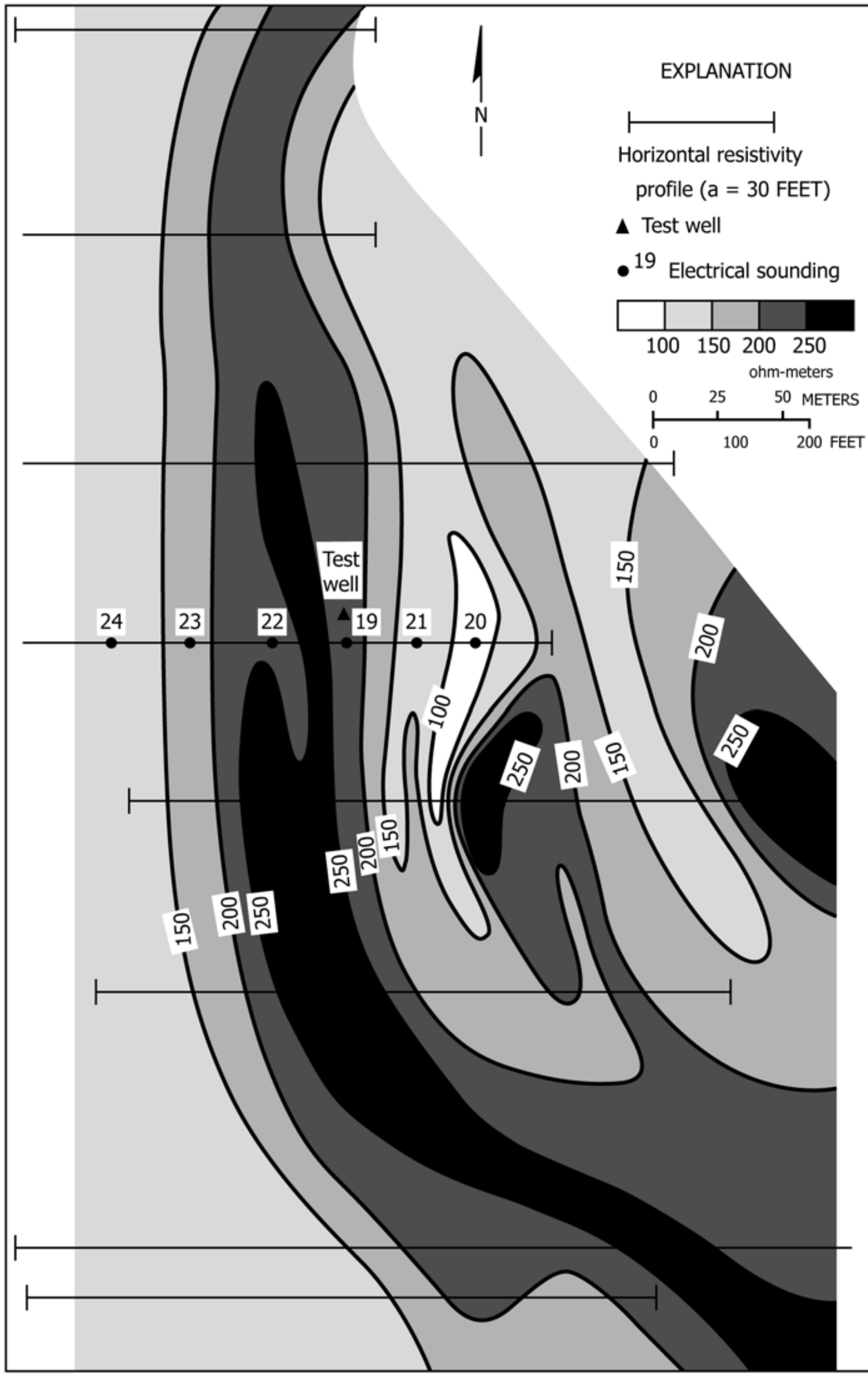

FIG. 8 Apparent Resistivity Contour Map (from Zohdy et al, (12))

Consideration should be given to the orientation of lines with respect to geologic features of interest, such as buried channels, faults, or fractures.

6.2.4.4 *Spacing*—Generally, the spacing between adjacent sounding or profile measurements is determined by the desired degree of lateral resolution. For reconnaissance measurements that do not require extensive detailed mapping of the layer(s) of interest, widely spaced measurements are used. For detailed surveys, more closely spaced measurements are required.

6.2.5 *Data Acquisition Format*—There is presently no recommended standard for resistivity data files.

6.3 *Implementation of Survey:*

6.3.1 *On-Site Check of Plan*—A systematic visual inspection of the site should be made upon arrival to determine if the initial survey plan is feasible. At this point, modifications to the survey plan may be required.

6.3.2 *Feasibility Test*—If a feasibility test has not been previously done, the results of initial measurements can be used to confirm the existence of an adequate resistivity contrast and can also be used to assess signal-to-noise ratio at the site. Results of the initial on-site tests may require that changes be made to the original survey plan.

6.3.3 *Survey Lines Layout:*

6.3.3.1 Locate the position for the resistivity lines based on the survey requirements.

6.3.3.2 Lay out the arrangement of wires and electrodes for the chosen array geometry in the field.

6.3.3.3 Drive the electrodes into the ground at correct intervals.

6.3.3.4 The electrodes must be in good electrical contact with the soil or rock. Improper placement of electrodes is a common problem resulting in low or erratic current measurement and noise.

6.3.4 *Check for Leakage*—A check for excessive current leakage should be made prior to making measurements:

6.3.4.1 Make a resistivity measurement with one current electrode disconnected and its wire insulated from the system.

6.3.4.2 Make a resistivity measurement with the first current electrode reconnected and the second current electrode disconnected.

6.3.4.3 Make a resistivity measurement with the apparatus connected normally

6.3.4.4 If either resistivity measurement with one current electrode disconnected is not at least one order-of-magnitude higher than with both current electrodes connected, then excessive current leakage exists and must be corrected before proceeding. Possible sources of current leakage include a ground in the instrument, split or cracked wire, or wet wire and equipment. Such current loss leads to errors in the measurements. To prevent current leakage, equipment and cables should be electrically insulated from highly resistive dry soil or moist soil.

6.3.5 *Ensure Good Electrode Contact*—Where the electrodes touch the ground, there is a contact resistance. If this contact resistance is high (particularly in dry or frozen soil), there will be a problem injecting current into the ground through the current electrodes and there may be contact polarization problems at the potential electrodes. To minimize these problems, the contact resistance can be lowered by wetting the soil around the electrodes with salt water or by placing multiple electrodes in the ground. However, placement and movement of the water near the electrodes can sometimes create polarization problems. It may be necessary to wet the ground near the electrodes and then wait a period of time until the electrodes stabilize with their wetted soil environment.

6.3.6 *Safety Precautions for the Survey:*

6.3.6.1 *Shock Hazard*—Electrical resistivity measurements use current sources and voltages that may result in shock hazard and possible electrocution to the operator, field personnel, and other persons. Adequate safety precautions should be taken to eliminate contact of personnel with measurement equipment, and wire and electrodes when the electrical current is flowing. At times when active measurements of electrical resistivity are not being made, the electrical current source should be physically disconnected from the wires going to the remainder of the equipment. All persons near the measurement should be made aware of when the current is flowing and when it is not. If there is danger of passersby accidentally encountering the electrodes, signs should be posted as a warning. Sufficient personnel should be on site to observe the entire electrode array and prevent contact by passersby.

6.3.6.2 *Electrical Storms*—Electrode arrays are well grounded to the earth and frequently are of a size to be likely targets for lightning. To protect the personnel and equipment, measurements should never be attempted during electrical storms.

6.4 *Interpretation of Resistivity Data:*

6.4.1 *General*—Both sounding and profiling data can be used in a qualitative, semi-quantitative, and quantitative manner.

6.4.1.1 In some limited cases, quantitative interpretation of the data is not required to provide the necessary results and a simple qualitative interpretation is sufficient. Examples of qualitative interpretation of profiling data are mapping the areal extent of a buried channel or a contaminant plume. A quantitative interpretation requires sounding data.

6.4.1.2 The level of effort involved in the interpretation depends upon the detail and accuracy desired which in turn determines the approach to interpretation. This guide does not attempt to review or summarize the available interpretation schemes, but provides references for them. A flow diagram for the interpretation process is shown in Fig. 9.

6.4.2 *Sounding Interpretation*—It is conventional practice to interpret sounding data quantitatively. An interpreted geoelectric section showing layer thickness, depths, and resistivity is constructed. In this process, apparent resistivity is converted to layer resistivity. For resistivity interpretation, the earth is assumed to consist of uniform horizontal layers. Curve matching and computer programs are available for interpretation. Interpretation by curve matching can be labor intensive. Computer-based interpretation (Zohdy and Bisdorf (**13**), and Zohdy (**12**,**14**)) offers many advantages, since it is often desirable to iterate through a number of interpretations in the process of converging upon the best solution. Hand-held programmable calculator programs are also available for solving the various resistivity formulas (Ballantyne et al (**15**)). Other programs are usually available from equipment manufacturers and software suppliers. Fig. 10 shows the results of resistivity sounding interpreted by a computer model.

6.4.2.1 Both forward and inverse models are available:

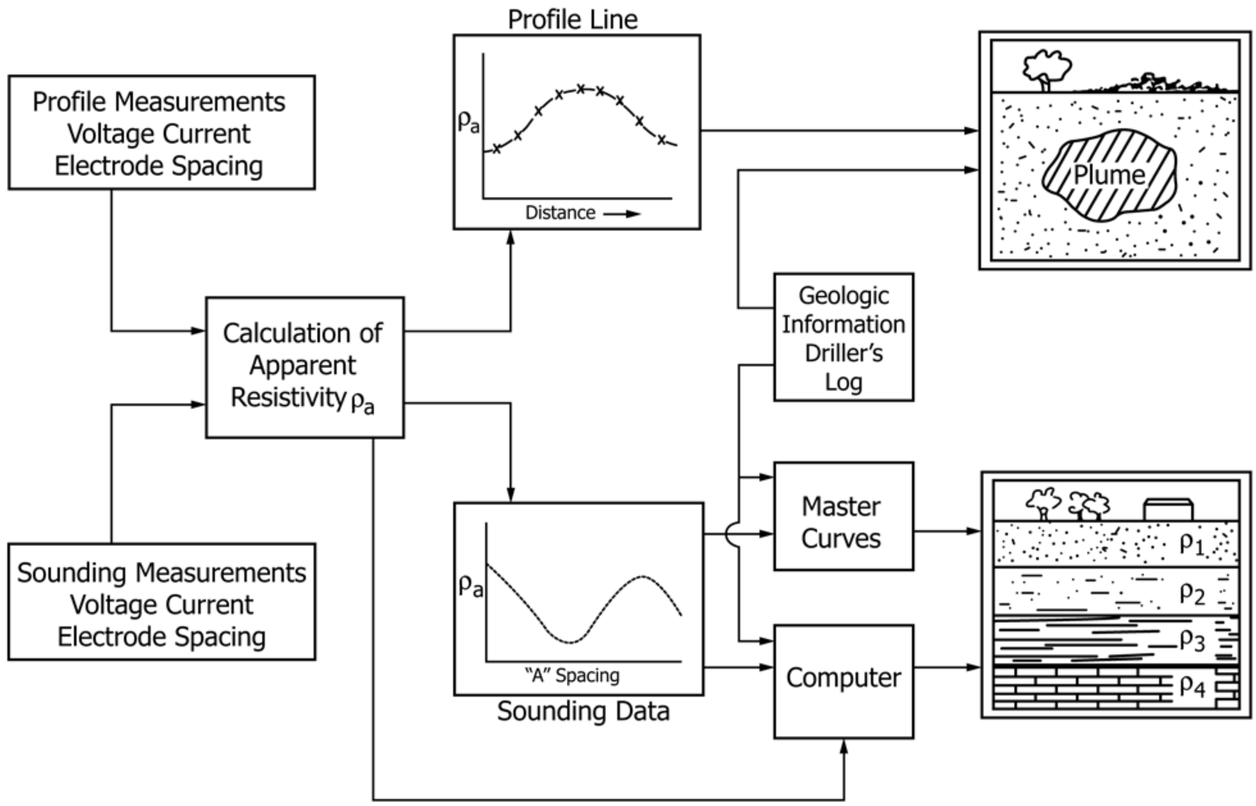

FIG. 9 Steps in Processing and Interpretation of Resistivity Data (from Benson et al, (8))

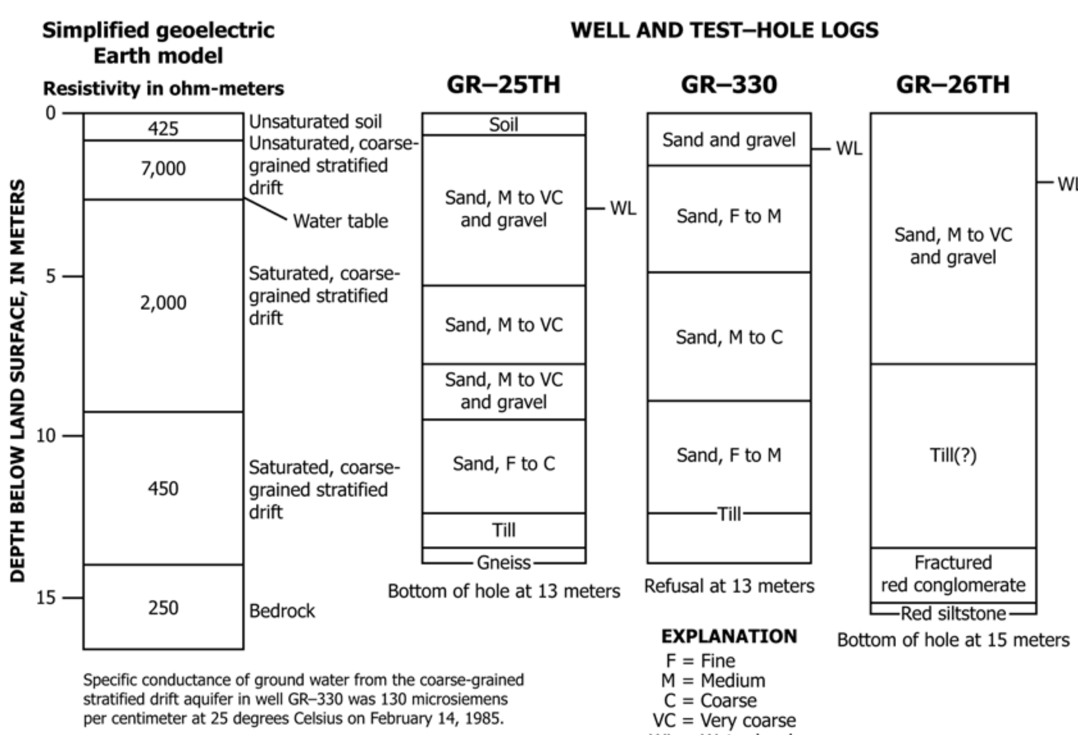

FIG. 10 Simplified Geoelectric Earth Model from Sounding Data (from Haeni, (16))

(1) A forward model predicts the sounding curve (apparent resistivity versus electrode spacing) for a given number of layers, their thickness, and resistivities.

(2) Inverse models use the field data (apparent resistivity versus electrode spacing) to generate a geoelectric section consisting of layer thicknesses and interpreted resistivities.

6.4.3 *Profile Interpretation*—Profiling data are bulk apparent resistivities, which are usually not converted to true resistivity values. Electrode spacing is selected to measure the resistivity at the depth of interest. Profiling data are often presented as a profile line (Fig. 6) or as a contour map (Fig. 8).

6.4.4 *Verification of Resistivity Interpretation*—Verification of resistivity interpretation should include correlation with available data. If supporting data are not available, this fact should be mentioned in the report.

6.4.4.1 A problem inherent in all geophysical studies is the nonunique correlation between possible geologic models and a single set of field data. This ambiguity can be resolved only through the use of sufficient ground-truth information along with geologic and geophysical information and experience of the interpreter.

6.4.4.2 Preliminary interpretation should be labelled as draft and treated with caution because it is easy to make errors in an initial field interpretation and a preliminary analysis is never a complete and thorough interpretation. Analysis in the field is done mostly as a means of quality control.

6.5 *Quality Control (QC)*—Quality control can be appropriately applied to resistivity measurements and is applicable to the field procedures, processing, and interpretation phases of the work. Good quality-control procedures require that standard procedures are followed and appropriate documentation is made.

6.5.1 The following items can be used to provide QC of field operations:

6.5.1.1 Documentation of the field procedures and interpretation methods that are planned to be used in the study.

6.5.1.2 A field log that records the field operational procedures used for the project.

6.5.1.3 Changes to the planned field procedures should be documented.

6.5.1.4 Conditions that could impact survey results should be documented (weather conditions and natural and cultural noise)

6.5.1.5 During or immediately after sounding data acquisition, a plot of apparent resistivity versus electrode spacing (Fig. 5) should be made to ensure that the data are of adequate quality and quantity (that is, a sufficient number of noise-free data points have been obtained to define the layers of interest).

6.5.1.6 During or immediately after profile data acquisition, a plot of apparent resistivity versus station location (Fig. 7) should be made to ensure that the data are of adequate quality and quantity (that is, a sufficient number of noise-free data points to define any lateral changes of interest in subsurface conditions).

6.5.1.7 If data are being recorded (by a computer or digital-acquisition system) with no visible means of observing the data, it is recommended that the data be reviewed as soon as possible to verify data quality.

6.5.1.8 If possible, a qualitative, on-site interpretation should be performed.

6.5.2 *Calibration and Standardization* —In general, the manufacturer's recommendations is followed for calibration and standardization. If no such recommendations are provided, a routine check of equipment should be made on a periodic basis and after each problem and repair. An operational check of equipment should be carried out before each project and before starting fieldwork each day.

6.5.2.1 The resistivity instrument(s) can be checked against a range of reference resistors that cover the resistance range of measurements made by the instrument.

7. Report

7.1 The following is a list of the key items that should be contained within most formal reports. In some cases, there is no need for an extensive formal report.

7.2 Report the following information:

7.2.1 Purpose and scope of the resistivity survey.

7.2.2 Geologic setting.

7.2.3 Limitations of the resistivity survey.

7.2.4 Assumptions made.

7.2.5 Field approach, including a description of the equipment and the data acquisition parameters used.

7.2.6 Location and orientation of the resistivity survey plotted on a site map.

7.2.7 Type of array (geometry) and number of electrodes used.

7.2.8 Location of center of the spread.

7.2.9 Orientation of the profile line.

7.2.10 Electrode spacing.

7.2.11 Any corrections applied to field data.

7.2.12 Results of field measurements:

7.2.12.1 Copies of raw data (optional), and

7.2.12.2 Plots of apparent resistivity versus electrical spacing (sounding) or apparent resistivity versus station location (profiling).

7.2.13 Method of interpretation used and specifically what analytical method(s) or software program(s) were used.

7.2.14 Interpreted results and any qualifications and alternate interpretations.

7.2.15 Format of recording data.

7.2.16 References for any supporting data used in the interpretation.

7.2.17 Persons responsible for the resistivity surveys and the data interpretation.

7.3 *Presentation of Data and Interpretation:*

7.3.1 Sounding data are often presented as single geoelectric section as shown in Fig. 11. If many soundings are made, the combined results may be presented as a geoelectric cross or as a contour map (that is, depth to water table, depth to rock, or depth to clay).

7.3.2 The results of a series of profile measurements can be shown as a profile or contour map. In either case, the values shown are apparent resistivity and should only be interpreted to indicate a change in subsurface conditions. If profile measurements are made at more than one electrode spacing, they may be presented as multiple profile lines or as multiple contour maps. Multiple profile lines can also be presented as a resistivity contour map.

7.3.3 The final resistivity interpretation generally leads to a conceptual model of site conditions (geologic, hydrologic, or cultural). A conceptual model is a simplified characterization of

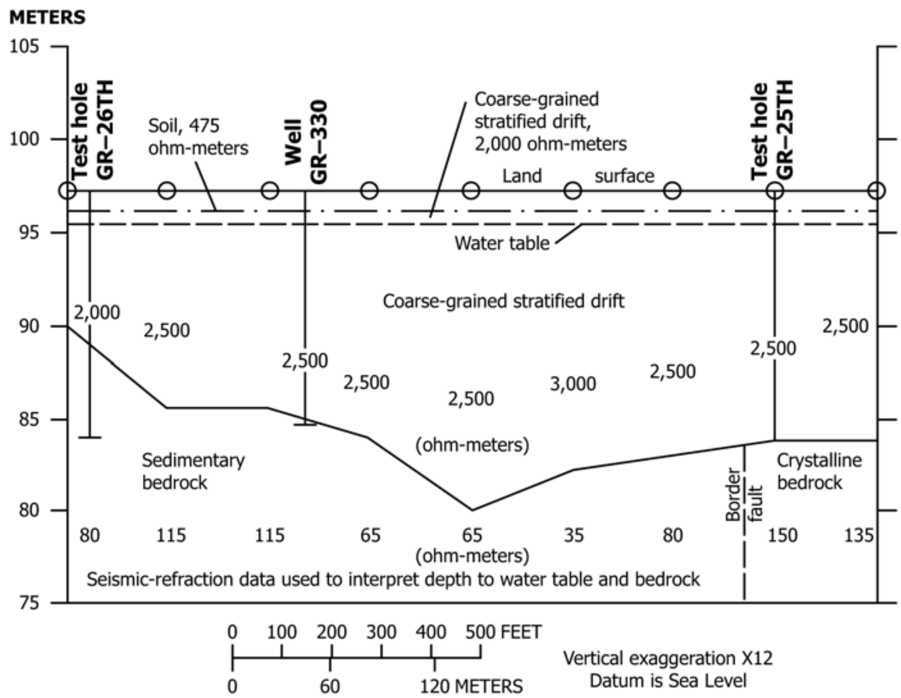

FIG. 11 Interpreted Geoelectric Section from Data in Fig. 10 (from Haeni, (16))

a site that incorporates all the essential features of the physical system under study. The conceptual model is usually shown as a cross section or contour map, or other drawings that illustrate the general geologic and hydrogeologic conditions along with any anomalous conditions.

8. Precision and Bias

8.1 *Bias*—For the purposes of this guide, bias is a measure of the closeness to the truth.

8.1.1 The bias with which the depth of a layer can be determined by the resistivity method depends on many factors. Some of these factors are:

8.1.1.1 Errors in field procedures, record keeping, processing, and interpretation,

8.1.1.2 Instrument errors in measuring and recording,

8.1.1.3 Field system geometry limitations, relating to electrode spacing and line location,

8.1.1.4 Topography,

8.1.1.5 Noise,

8.1.1.6 Variation of the earth from simplifying assumptions used in the resistivity sounding interpretation procedure,

8.1.1.7 Site-specific geologic limitations, such as high-resistivity soils and variable surface soil conditions, and

8.1.1.8 Ability and experience of the field crew and interpreter.

8.1.2 Published references indicate that the depth to a layer can reasonably be determined to within 30 % of the layer depth using the resistivity method. Large errors are usually due to improper interpretation, difficult field situations, inherent limitations of the method, or to the differences between depth to rock measurements from resistivity and drilling methods.

8.1.3 *Lateral Geologic Variability* —Agreement between resistivity sounding and borehole measurements may vary considerably along the survey line depending upon lateral geologic changes, such as, structure or the degree of weathering and fracturing in the rock. It is not always possible to have exact agreement between resistivity and borehole data along a survey line.

8.1.4 The bias of a resistivity profile is its ability to delineate a feature and is dependent upon measurement station spacing.

8.2 *Precision*—Precision is defined as a measure of the repeatability between measurements. Precision of a resistivity measurement will be affected by the contact resistance of the electrodes, location of the electrodes, soil moisture, and the level and variations of the temporal noise affecting the measurements. If a resistivity survey is repeated under identical conditions, the results would be expected to have a high level of precision.

8.3 *Resolution*—Resistivity measurements are inherently a bulk measurement and integrate a large volume of subsurface materials that increases for successively larger electrode spacings (deeper measurements).

8.3.1 *Lateral Resolution*—Lateral resolution of a resistivity survey is determined by the electrode spacing and by the distance between soundings or profile measurements. Closely spaced measurements will provide higher lateral resolution.

8.3.2 *Vertical Resolution*—Vertical resolution is how small a change in depth and how thin a layer can be detected by the resistivity method. The degree of vertical resolution that can be achieved is a complex function of the depth and thickness of the layers of interest and their resistivity contrasts. Some estimates of resolution can be made by the use of forward models. The resistivity method can typically resolve three layers and sometimes more.

9. Keywords

9.1 electrical method; geophysics; resistivity; subsurface investigation; surface geophysics

REFERENCES

(1) Keller, G. V., and Frischknecht, F. C., *Electrical Methods in Geophysical Prospecting*, US Environmental Protection Agency 1993, *Use of Airborne Surface and Borehole Geophysical Techniques at Contaminated Sites:* A Reference Guide, EPA/625/92/007. Pergamon, NY, 1966, 517 pp.

(2) Zohdy, A. A., Eaton, G. P., and Mabey, D. R., *Application of Surface Geophysics to Ground Water Investigations, U.S. Geological Survey, Techniques of Water Resources Investigation*, Book 2, Chapt. D1, 1974, 116 pp.

(3) Koefoed, O., *Geosounding Principles, 1, Resistivity Sounding Measurements*, Elsevier, NY, 1979, 276 pp.

(4) U.S. Environmental Protection Agency, 1993, *Use of Airborne, Surface, and Borehole Geophysical Techniques at Contaminated Sites: A Reference Guide*, EPA/625/92/007.

(5) Ward, S.H., "Resistivity and Induced Polarization Methods," *Geotechnical and Environmental Geophysics*, S.H. Ward, ed., Society of Exploration Geophysicists, Tulsa, OK, Vol I, 1990, pp. 147-190.

(6) Griffiths, D. H., and King, R. F., *Applied Geophysics for Engineers and Geologists*, Pergamon Press, 1981.

(7) Telford, W. M., Geldart, L. P., Sheriff, R. E., and Keys, D. A., *Applied Geophysics* , 2nd ed., Cambridge University Press, New York, NY, 1990, 770 pp.

(8) Benson, R., Glaccum, R.A., and Noel, M.R., *Geophysical Techniques for Sensing Buried Wastes and Waste Migration*, National Water Well Association, Dublin, OH, 1988, 236 pp.

(9) Sheriff, Robert E., *Encyclopedic Dictionary of Exploration Geophysics, 3rd ed.*, Society of Exploration Geophysicists, Tulsa, OK, 1991, 323 p. and Bates, R. L., and Jackson, J. A., *Glossary of Geology*, 1980.

(10) McNeill, J.D., "Use of Electromagnetic Methods for Ground Water Studies," *Geotechnical and Environmental Geophysics*, S. H. Ward, ed., Society of Exploration Geophysicists, Tulsa, OK, Vol 1, 1990, pp. 192-218.

(11) Lane, J.W., Jr., Haeni, F.P., and Watson, W.M., "Use of a Square-Array Direct-Current Resistivity Method to Detect Fractures in Crystalline Bedrock in New Hampshire," *Ground Water*, Vol 33, 1995, pp. 476-485.

(12) Zohdy, A. A. R., *A Computer Program for the Automatic Interpretation of Schlumberger Sounding Curves over Horizontally Stratified Media*, NTIS PB-232-703, 1974, 25 pp.

(13) Zohdy, A. A. R., and Bisdorf, R. J., *Computer Programs for the Forward Calculation and Automatic Inversion of Wenner Sounding Curves*, NTIS PB-247-265, 1975, 38 pp.

(14) Zohdy, A. A. R., *Automated Interpretation of Schlumberger Sounding Curves Using Modified Dar Zarrouk Functions, U.S. Geological Survey Bulletin 1313-E,* 1975, 39 pp.

(15) Ballantyne, Edwing J., Jr., Campbell, D. L., Mentermeier, S. H., and Wiggins, R., *Manual of Geophysical Hand-Calculator Programs*, Society of Exploration Geophysicists, Tulsa, OK, 1981.

(16) Haeni, F.P., *Application of Surface Geophysical Methods to Investigations of Sand and Gravel Aquifers in the Glaciated Northeastern United States, U.S. Geological Survey Professional Paper 1415-A*, 1995, 70 pp.

(17) Bates, R. L. and J. A. Jackson, 1980, *Glossary of Geology*. American Geological Institute.

(18) Dobrin, M. B. and C. H. Savit, 1988. *Introduction to Geophysical Prospecting, Fourth Edition*. McGraw-Hill, New York, 867 p.

(19) Orellana, E. and Mooney, H. M. 1966. *Master Tables and Curves for Vertical Electrical Sounding Over Layered Structures* . Madrid, Interciencia, 150p, 66 tables.

(20) Orellana, E. and Mooney, H. M., 1972. *Two and Three Layer Master Curves and Auxiliary Point Diagrams for Vertical Electrical Sounding Using Wenner Arrangement*. Madrid, Interciencia, 41p.

(21) Zohdy, A. A. R., 1980, *Master Curves of Schlumberger Soundings Over Three Vertical Layers, Array Expanded at Right Angles to Strike*. U.S. Geological Survey Open File Report OF80-249, 166p.

ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.

This standard is copyrighted by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (www.astm.org). Permission rights to photocopy the standard may also be secured from the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, Tel: (978) 646-2600; http://www.copyright.com/