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IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System

Sponsor

**Power System Instrumentation and Measurements Committee
of the
IEEE Power Engineering Society**

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Foreword

(This Foreword is not a part of IEEE Std 81-1983, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System.)

In order to increase its practical usefulness, this guide has been divided into two parts. Part I, *Normal Measurements*, covers the majority of field measurements which do not require special high-precision equipment and measuring techniques, and which do not encounter unusual difficulties such as may be found with extensive grounding systems, abnormally high stray ac or dc currents, etc. Part I has been extensively revised and updated. Part II, *Special Measurements*, is to be completed in the future. This part is intended to describe the methods of measurements applicable when unusual difficulties make normal measurements either impractical or inaccurate. Very large power station ground grids and counterpoises of transmission lines are examples of such grounding systems.

This guide was prepared by the Earth Resistivity, Ground Impedance, and Earth Surface Potential Measurement Working Group of the RLC Subcommittee, Power System Instrumentation and Measurements Committee. The working group's members at the time the guide was prepared were:

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CLAUSE	PAGE
1. Purpose.....	1
1.1	1
1.2	1
2. Scope.....	2
2.1	2
2.2	2
2.3	2
3. Objectives of Tests.....	2
3.1	2
3.2	2
3.3	2
4. Definitions.....	3
5. Safety Precautions While Making Ground Tests	4
5.1 Station Ground Tests.....	4
5.2 Surge-Attester Ground Tests.....	5
5.3 Small Isolated Ground Tests	5
6. General Considerations of the Problems Related to Measurements	5
6.1 Complexities	5
6.2 Test Electrodes.....	5
6.3 Stray Direct Currents	6
6.4 Stray Alternating Currents	7
6.5 Reactive Component of Impedance of a Large Grounding System.....	7
6.6 Coupling Between Test Leads	7
6.7 Buried Metallic Objects	7
7. Earth Resistivity	8
7.1 General	8
7.2 Methods of Measuring Earth Resistivity	10
7.3 Interpretation of Measurements	13
7.4 Instrumentation	16
8. Ground Impedance	16
8.1 General	16
8.2 Methods of Measuring Ground Impedance.....	18
8.3 Testing the Integrity of the Ground Grid	23
8.4 Instrumentation	24
9. Earth Potential.....	24
9.1 Equipotential Lines	24
9.2 Potential Contour Surveys	25
9.3 Step and Touch Voltages	25

CLAUSE	PAGE
10. Transient Impedance	27
10.1 Transient Impedance of Ground Systems	27
11. Model Tests	29
11.1 Purpose	29
11.2 Similarity Criteria and Limitations	29
11.3 Instrumentation	29
11.4 Resistance Measurements	30
11.5 Potential Measurements	30
11.6 Interpretation of Measurements	30
12. Instrumentation	31
12.1 Ratio Ohmmeter	31
12.2 Double-Balance Bridge	32
12.3 Single-Balance Transformer	33
12.4 Ammeter-Voltmeter	34
12.5 Induced Polarization Units	34
12.6 High-Frequency Earth Resistance Meter	35
13. Practical Aspects of Measurements	36
13.1 Selection of Auxiliary Electrodes	36
13.2 Selection of Test Leads	37
13.3 Selection of Auxiliary Equipment	37
13.4 Testing Precautions	38
13.5 Large Substations	39
Annex A Nonuniform Soils (Informative)	40
Annex B Determination of an Earth Model (Informative)	42
Annex C Theory of the Fall of Potential Method (Informative)	44
Annex D Bibliography (Informative)	47

IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System

Part I Normal Measurements

1. Purpose

1.1

It is the purpose of this guide to describe and discuss the present state of the technique of measuring ground resistance and impedance, earth resistivity, potential gradients from currents in the earth, and the prediction of the magnitudes of ground resistance and potential gradients from scale model tests. Factors influencing the choice of instruments and the techniques for various types of measurements are covered. These include the purpose of the measurement, the accuracy required, the type of instruments available, possible sources of error, and the nature of the ground or grounding system under test.

1.2

The guide is intended to assist the engineer or technician in obtaining and interpreting accurate, reliable data. It describes test procedures which promote the safety of personnel and property, and prevent interference with the operation of neighboring facilities.

2. Scope

2.1

The testing methods covered in this guide include:

- 1) The measurement of the resistance and impedance to earth of electrodes varying from small rods and plates to large grounding systems of stations.
- 2) Ground. potential surveys, including the measurement of step and touch voltages, and potential contour surveys.
- 3) Scale-model tests for laboratory determination of the ground resistance and potential gradients for an idealized design.
- 4) The measurement of earth resistivity.

2.2

The methods covered herein are limited to those using direct current, periodically reversed direct current, alternating sinusoidal current and impulse currents (for measuring transient impedances). This guide does not propose to cover all possible test signals and test methods.

2.3

Extreme precision is not always possible because of the many variables encountered; therefore, the measurements should be carefully made by the most suitable method available, with a thorough understanding of the possible sources of error.

3. Objectives of Tests

3.1

Measurements of ground resistance or impedance and potential gradients on the surface of the earth due to ground currents are necessary to:

- 1) Verify the adequacy of a new grounding system
- 2) Detect changes in an existing grounding system
- 3) Determine hazardous step and touch voltages
- 4) Determine ground potential rise (GPR) in order to design protection for power and communication circuits.

3.2

Scale-model tests are useful in studying or developing new designs for grounding systems which cannot be adequately studied by analytical methods (complex shape or complex soil structure).

3.3

Earth resistivity measurements are useful for:

- 1) Estimating the ground resistance of a proposed substation or transmission tower
- 2) Estimating potential gradients including step and touch voltages
- 3) Computing the inductive coupling between neighboring power and communication circuits

- 4) Designing cathodic protection systems
- 5) Geological surveys

4. Definitions

Definitions of terms pertinent to the subject matter are listed here. Those approved or standardized by other bodies are used wherever possible.

Definitions as given herein apply specifically to the application of this guide. For additional definitions see ANSI/IEEE Std 100-1977, IEEE Standard Dictionary of Electrical and Electronics Terms.

ground: A conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth, or to some conducting body of relatively large extent that serves in place of the earth.

NOTE — It is used for establishing and maintaining the potential of the earth (or of the conducting body) or approximately that potential, on conductors connected to it, and for conducting ground current to and from the earth (or the conducting body).

grounded: A system, circuit, or apparatus referred to is provided with a ground.

ground-return circuit: A circuit in which the earth is utilized to complete the circuit.

ground current: Current flowing in the earth or in a grounding connection.

grounding conductor: The conductor that is used to establish a ground and that connects an equipment, device, wiring system, or another conductor (usually the neutral conductor) with the grounding electrode or electrodes.

grounding electrode: A conductor used to establish a ground.

grounding connection: A connection used in establishing a ground and consists of a grounding conductor, a grounding electrode and the earth (soil) that surrounds the electrode or some conductive body which serves instead of the earth.

ground grid: A system of grounding electrodes consisting of interconnected bare cables buried in the earth to provide a common ground for electrical devices and metallic structures.

NOTE — It may be connected to auxiliary grounding electrodes to lower its resistance.

ground mat: A system of bare conductors, on or below the surface of the earth, connected to a ground or a ground grid to provide protection from dangerous touch voltages.

NOTE — Plates and gratings of suitable area are common forms of ground mats.

grounding system: Consists of all interconnected grounding connections in a specific area.

ground resistance (grounding electrode): The ohmic resistance between the grounding electrode and a remote grounding electrode of zero resistance.

NOTE — By *remote* is meant at a distance such that the mutual resistance of the two electrodes is essentially zero.

mutual resistance of grounding electrodes: Equal to the voltage change in one of them produced by a change of one ampere of direct current in the other, and is expressed in ohms.

electric potential: The potential difference between the point and some equipotential surface, usually the surface of the earth, which is arbitrarily chosen as having zero potential (remote earth).

NOTE — A point which has a higher potential than a zero surface is said to have a positive potential; one having a lower potential has a negative potential.

equipotential line or contour: The locus of points having the same potential at a given time.

potential profile: A plot of potential as a function of distance along a specified path.

surface-potential gradient: The slope of a potential profile, the path of which intersects equipotential lines at right angles.

touch voltage: The potential difference between a grounded metallic structure and a point on the earth's surface separated by a distance equal to the normal maximum horizontal reach, approximately one meter.

step voltage: The potential difference between two points on the earth's surface, separated by a distance of one pace, that will be assumed to be one meter, in the direction of maximum potential gradient.

NOTE — This potential difference could be dangerous when current flows through the earth or material upon which a workman is standing, particularly under fault conditions.

resistivity (material): A factor such that the conduction-current density is equal to the electric field in the material divided by the resistivity.

coupling: The association of two or more circuits or systems in such a way that power or signal information may be transferred from one to another.

NOTE — Coupling is described as close or loose. A close-coupled process has elements with small phase shift between specified variables; close-coupled systems have large mutual effect shown mathematically by cross-products in the system matrix.

coupling capacitance: The association of two or more circuits with one another by means of capacitance mutual to the circuits.

resistive coupling: The association of two or more circuits with one another by means of resistance mutual to the circuits.

direct coupling: The association of two or more circuits by means of self-inductance, capacitance, resistance, or a combination of these that is common to the circuits.

inductive coupling (1) (communication circuits): The association of two or more circuits with one another by means of inductance mutual to the circuits or the mutual inductance that associates the circuits.

NOTE — This term, when used without modifying words, is commonly used for coupling by means of mutual inductance, whereas coupling by means of self-inductance common to the circuits is called direct inductive coupling.

(2) (inductive coordination practice): The interrelation of neighboring electric supply and communication circuits by electric or magnetic induction, or both.

effective resistivity: A factor such that the conduction current density is equal to the electric field in the material divided by the resistivity.

counterpoise (overhead lines) (lighting protection): A conductor or system of conductors, arranged beneath the transmission line, located on, above or most frequently below the surface of the earth, and connected to the footings of the towers or poles supporting the line.

5. Safety Precautions While Making Ground Tests

5.1 Station Ground Tests

It should be strongly impressed on all test personnel that a lethal potential can exist between the station ground and a remote ground if a power-system fault involving the station ground occurs while ground tests are being made.

Since one of the objectives of tests on a station-ground system is to establish the location of remote earth for both current and potential electrodes, the leads to these electrodes must be treated as though a possible potential could exist between test leads and any point on the station ground grid. Some idea of the magnitude of this possible potential may be gained from the consideration that even in the larger stations the ground grid shall have an impedance in the order of $0.05\ \Omega$ to $0.5\ \Omega$. Assuming for this example that the ground-fault current through the grid is in the order of 20 kA the potential to remote earth (ground potential rise) will be in the order of 1.0 kV to 10 kV. For higher ground impedance or greater fault currents, the rise of station-ground voltage may exceed 10 kV.

The preceding discussion points to the necessity of caution when handling the test leads, and under no circumstances should the two hands or other parts of the body be allowed to complete the circuit between points of possible high-potential difference. It is true that the chances are remote that a station-ground fault will occur while test leads are being handled, but this possibility should not be discounted and therefore the use of insulating shoes, gloves, blankets, and other protection devices are recommended whenever measurements are carried out at an energized power station.

In all cases, safety procedures and practices adopted by the particular organization involved shall be followed.

5.2 Surge-Attester Ground Tests

These grounds fall in a special category because of the extremely high short-duration lightning currents carried by surge-arrester grounds. These currents may be in excess of 50 000 A for surge currents, with a possibility of fault-system currents in the case of a defective surge arrester. An isolated surge arrester ground should never be disconnected to be measured, since the base of the arrester can be elevated to the line potential. A surge-arrester ground can be tested as long as precautions are taken to minimize arrester discharge.

5.3 Small Isolated Ground Tests

Another precaution concerns possible high-potential gradients around the current electrode. If current is passed into a remotely located electrode, as in the fall-of-potential method, it is worthwhile to ensure against a curious person being allowed near the current electrode while tests are in progress. Similarly, in rural areas grazing animals should not be allowed near the test current electrode.

6. General Considerations of the Problems Related to Measurements

6.1 Complexities

The measurements of earth resistivities, ground impedances, and potential gradients introduce a number of complexities not encountered in other resistance, impedance, and potential measurements.

It may be necessary to make multiple measurements and to plot trends. Stray currents and other factors usually interfere with the measurements.

With development and industrial growth adjacent to power substations, it becomes increasingly difficult to choose a suitable direction or locations for test probes to make a resistance test. Moreover, the connection of overhead ground wires, buried water pipes, cable sheaths, etc, all have the effect of physically distorting and enlarging the ground grid.

NOTE — Overhead ground wires may be insulated either deliberately or by clamp corrosion and therefore low-voltage tests may give answers different from actual fault tests.

Ground impedance measurements should be made immediately after the ground grid has been installed to be certain that there are no major omissions of grounded components normally connected into the ground grid. Future installations such as water pipes, rail, etc will alter the values.

It should be noted, however, that the ground impedance will usually decrease as the earth settles to a uniform compactness perhaps a year after installation.

6.2 Test Electrodes

The ground-impedance measurement methods described in the following sections require the use of current and voltage test electrodes.

If the impedance measurement method used is the two- or three-point method, the impedance of the test electrodes should be either negligible with respect to that of the ground being tested (two-point method) or of the same order of magnitude as the ground being tested (three-point method). Otherwise, incorrect results may be obtained.

Obviously, these restrictions limit the use of such methods to grounds of relatively small extent such as residential swimming pools and small low-voltage distribution substation grounds.

In the case of impedance measurements using the fall-of-potential method, the requirements of the test electrodes are not so critical.

Theoretically the ground resistances of the test electrodes do not influence the measurements since these are taken into consideration by the method of measurement. In practice, however, the resistance values should not exceed a maximum value beyond which there is insufficient test current in the measuring instrument. By insufficient test current is meant:

- 1) *Current lower than the instrument sensitivity, or*
- 2) *Current in the order of magnitude of the stray currents in the earth*
- 3) *Or both (1) and (2)*

In case (1), the only corrective action available at the site of measurement is to increase the test current. This can be done by either increasing the voltage of the power supply or by decreasing the test electrode resistances. Increasing the power supply voltage is not always possible especially with hand-driven generators incorporated in the measuring instrument. When this solution is practical, care must be taken to avoid dangerous potentials of the electrodes and test leads. A maximum of 100 V is considered safe if special precautions (such as use of insulating gloves or shoes) are taken.

Often the most effective way of increasing the test current is to decrease the current electrode resistance. This can be done by driving the rod deeper into the soil, pouring water around the rod, or by driving additional rods and interconnecting them in parallel. The addition of salt to the water poured around the test electrodes is of very little value; the moisture is the main requirement.

As a general rule the resistance values of the current and potential electrodes should meet the requirements of the instruments used. With commercial instruments, a potential electrode resistance of 1000 Ω may be used. Some manufacturers claim that their instrument will permit 10 000 Ω in the potential electrode.

The current electrode resistance should usually be less than 500 Ω . This resistance value is a function of the voltage generated by the power supply and the desired test current. The ratio of the generated voltage to the current electrode resistance determines the test current flowing in the current-indicating element of the instrument being used. As a rule of thumb the ratio between the current electrode resistance and the ground resistance being tested should never exceed 1000 to 1, preferably 100 to 1 or less.

In case (2), when dc tests are being made, the test current must be increased to overcome the interfering effects of stray dc earth currents. When tests with ac or periodically reversed dc signals are being made, the frequency of the test signal may be set to a frequency not present in the stray currents.

6.3 Stray Direct Currents

Conduction of electricity in the soil is electrolytic and direct current results in chemical action and polarization potential difference. Direct potentials are produced between various types of soil and between soil and metal by galvanic action. Galvanic potentials, polarization, and, if present, stray direct currents may seriously interfere with direct-current measurements. Therefore, periodically reversed direct current or sometimes a regularly pulsed current is used in making measurements. However, when using periodically reversed direct current for resistance measurements

the resulting values will be fairly close, but they may not be accurate for alternating-current applications. Caution must be exercised in areas subject to solar-induced currents (quasi-dc).

6.4 Stray Alternating Currents

Stray alternating currents in the earth, in the grounding system under test, and in the test electrodes present an additional complication. The effects of stray alternating current may be mitigated in ground resistance measurements by utilizing a frequency that is not present in the stray current. Most measuring devices use frequencies within a range of 50 Hz to 100 Hz. The use of filters or narrow band measuring instruments, or both, is often required to overcome the effects of stray alternating currents.

6.5 Reactive Component of Impedance of a Large Grounding System

The impedance of a large grounding system may be extremely low (for example, $0.010\ \Omega$) but it may have a significant quadrature component [B23]¹. Certain precautions should be taken when measuring the 60 Hz impedance of a large grounding system. For such measurements the test device should be operated at an approximate system frequency of 60 Hz, but the test frequency should be slightly above or below 60 Hz, using a minimum of 50 A for the most accurate results and to avoid 60 Hz ground currents. Part II of this guide², *Special Measurements*, will cover impedance measurements of large grounding systems.

6.6 Coupling Between Test Leads

The effect of coupling between the test leads becomes important when measuring low values of ground impedance. Any voltage produced in the potential lead due to coupling from current flowing in the current lead is directly additive to the desired measured voltage and produces a measurement error. Since the 60 Hz inductive coupling between two parallel test leads may be as high as $0.1\ \Omega/100\text{ m}$, the error can be appreciable. Low ground impedance usually is found with a large area ground, which requires long test leads to reach remote earth.

Conversely, a small area ground usually has fairly high ground impedance and requires shorter test leads to reach remote earth. Thus the effects of coupling can be expected to be worse on measurements of large area, low impedance grounds. As a rule of thumb test lead coupling is usually negligible on measurements of grounds of $10\ \Omega$ or greater, is almost always important on measurements of $1\ \Omega$ or less, and should be considered in the range between 1 and $10\ \Omega$.

Test lead coupling may be minimized by appropriately routing the potential and current leads. When test lead couplings are anticipated, the potential and current leads should be placed at the maximum feasible angle.

6.7 Buried Metallic Objects

Partially or completely buried objects such as rails, water, or other industrial metallic pipes will considerably influence the measurement results [B9], [B36].

In earth-resistivity tests a sharp drop in the measured value is often caused by the presence of a metallic object buried close to the test location. The magnitude and extent of the drop gives an idea of the importance and depth of the buried material. The measured resistance of a ground electrode located close to a buried metallic object can be significantly lower than its value if the additional buried metal objects were not present. However, the importance of the effect of buried metallic structures should not be minimized in determining the effective GPR for communication protective purpose. Earth potential contours are distorted and gradients are increased when measured above buried metallic objects.

¹The numbers in brackets correspond to those of the Bibliography listed in Appendix D of this guide.

²Part II of this guide has not been completed at this time.

Wherever the presence of buried metallic structures is suspected in the area where soil resistivity measurements are to be taken and the location of these structures is known, the influence of these structures on the soil resistivity measurement results can be minimized by aligning the test probes in a direction perpendicular to the routing of these structures. Also the location of the test probes should be as far as possible from the buried structures.

7. Earth Resistivity

7.1 General

The techniques for measuring soil resistivity are essentially the same whatever the purpose of the measurement. However, the interpretation of the recorded data can vary considerably, especially where soils with non-uniform resistivities are encountered. The added complexity caused by nonuniform soils is common, and in only a few cases are the soil resistivities constant with increasing depth.

Earth resistivity varies not only with the type of soil but also with temperature, moisture, salt content, and compactness (see Fig 1). The literature indicates that the values of earth resistivity vary from 0.01 to 1 $\Omega\cdot\text{m}$ for sea water and up to $10^9 \Omega\cdot\text{m}$ for sandstone. The resistivity of the earth increases slowly with decreasing temperatures from 25 °C to 0 °C. Below 0 °C the resistivity increases rapidly. In frozen soil, as in the surface layer in winter the resistivity may be exceptionally high.

Table 1 shows the resistivity values for various soils and rocks. This table has the advantage of being simple. More detailed tables are available in [B31], [B36], [B39].

Usually there are several layers, each having a different resistivity. Lateral changes may also occur, but in general, these changes are gradual and negligible at least in the vicinity of the site concerned.

In most cases, the measurement will show that the resistivity ρ_a is mainly a function of depth z . For purposes of illustration, we will assume that this function may be written as:

$$\rho_a = \phi(z) \quad (1)$$

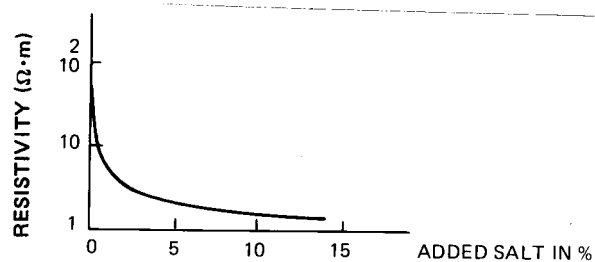
The nature of the function Φ is in general not simple and consequently the interpretation of the measurements will consist of establishing a simple equivalent function Φ_e which will give the best approximation. In the case of power and communication circuits, a two horizontal layer configuration [B10], [B18], [B20], [B31], [B38], [B39], and an exponential earth [B38], [B42] have proved to be good approximations that can be useful in determining system designs.

Some publications [B9], [B10], [B18], [B20], [B31], [B36], [B38], [B39], [B42], have shown that earth surface potential gradients inside or adjacent to an electrode are mainly a function of top soil resistivity. In contrast, the ground electrode resistance is primarily a function of deep soil resistivity, especially if the electrode is very large.

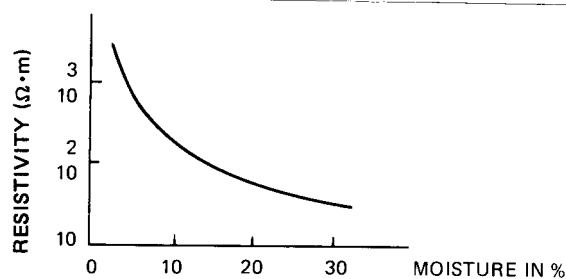
NOTE — This is not valid in those extreme cases where the electrode is buried in an extremely high resistivity top soil.

Transmission-line parameters at power frequencies are sensitive to the presence of layers of different resistivities. However, at power-line carrier frequencies, radio, or surge frequencies, earth return impedances are practically sensitive only to the top few meters of soil.

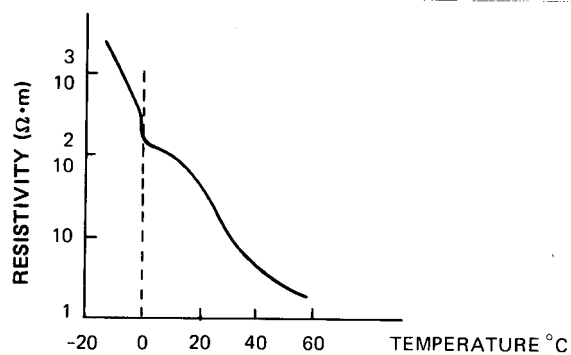
The above statements are good arguments in favor of methods which include both surface and deep soil-resistivity measurements. In such methods a number of readings are taken. At each reading the test current involves an increased volume of the surrounding earth.



(a)



(b)



(c)

Figure 1—Earth Resistivity Variations
(a) Salt (b) Moisture (c) Temperature

Table 1—Geological Period and Formation

Earth Resistivity Ohmmeters	Quaternary	Cretaceous Tertiary Quaternary	Carboniferous Triassic	Cambrian Ordovician Devonian	Pre-Cambrian and Combinat. with Cambrian
1 Sea water					
10 Unusually low		Loam			
30 Very low		Clay			
100 Low		Chalk	Chalk		
300 Medium			Trap		
1000 High			Diabase		
			Shale		
			Limestone	Shale	
			Sandstone	Limestone	
				Sandstone	Sandstone
3000 Very High	Coarse Sand			Dolomite	Quartzite
	and Gravel				Slate
10 000 Unusually high	in surface				Granite
	Layers				Gneisses
NOTE — Table 1 is from reference [B38] of the Bibliography section.					

7.2 Methods of Measuring Earth Resistivity

7.2.1 Geological Information and Soil Samples

Often, at the site where a grounding system is to be installed, extensive civil engineering work must be carried out. This work usually involves geological prospecting which results in a considerable amount of information on the nature and configuration of the site soil. Such data could be of considerable help to the electrical engineer who should try to obtain this information.

The determination of soil resistivity from the values of resistance measured between opposite faces of a soil sample of known dimensions is not recommended since the unknown interfacial resistances of the soil sample and the electrodes are included in the measured value.

A more accurate determination is possible if a four-terminal resistance measurement of the soil sample is made. The potential terminals should be small, relative to the sample cross-section, and located sufficiently distant from the current terminals to assure near-uniform current distribution across the sample. A distance equal to the larger cross-section dimension is usually adequate for the purpose of the determination.

It is difficult, and in some cases impossible, to obtain a useful approximation of soil resistivity from resistivity measurements on samples. This is due to the difficulty of obtaining representative, homogeneous soil samples, and in duplicating the original soil compaction and moisture content in the test cell.

7.2.2 Variation of Depth Method

This method, sometimes called a three-point method, is a ground-resistance test carried out several times, each time the depth of burial of the tested electrode is increased by a given increment. The purpose of this is to force more test current through the deep soil. The measured resistance value will then reflect the variation of resistivity at increased depth. Usually the tested electrode is a rod. Rods are preferred to other types of electrodes because they offer two important advantages:

- 1) The theoretical value of ground-rod resistance is simple to calculate with adequate accuracy, therefore, the results are easy to interpret.
- 2) The driving of a rod into the soil is normally an easy operation.

The above measurements can be carried out using one of the methods described in 8.2. One should bear in mind, however, that the measured value of the resistance should be as accurate as possible so that it can be successfully compared to the theoretical value. Therefore, the fall-of-potential method is preferably used for these measurements.

The variation of depth method gives useful information about the nature of soil in the vicinity of the rod (5 to 10 times the rod length). If a large volume of soil must be investigated, it is preferable to use the four-point method, since the driving of long rods is not practical.

7.2.3 Two-Point Method

Rough measurements of the resistivity of undisturbed earth can be made in the field with the shepard-soil resistivity meter and similar two-point methods. The apparatus consists of one small and one smaller iron electrode, both attached to an insulating rod. The positive terminal of a battery is connected through a milliammeter to the smaller electrode and the negative terminal to the other electrode. The instrument can be calibrated to read directly in ohm-centimeters at nominal battery voltage. This type of apparatus is easily portable and with it a number of measurements can be made in a short time on small volumes of soil by driving the electrodes in the ground or in the walls or bottom of excavations.

7.2.4 Four-Point Method

The most accurate method in practice of measuring the average resistivity of large volumes of undisturbed earth is the four-point method [B43]. Small electrodes are buried in four small holes in the earth, all at depth b and spaced (in a straight line) at intervals a . A test current I is passed between the two outer electrodes and the potential V between the two inner electrodes is measured with a potentiometer or high-impedance voltmeter. Then V/I gives the resistance R in ohms.

Two different variations of the four-point method are often used:

- 1) *Equally Spaced or Wenner Arrangement.* With this arrangement the electrodes are equally spaced as shown in Fig 3(a). Let a be the distance between two adjacent electrodes. Then, the resistivity ρ in the terms of the length units in which a and b are measured is:

$$\rho = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \quad (2)$$

It should be noted that this does not apply to ground rods driven to depth b ; it applies only to small electrodes buried at depth b , with insulated connecting wires. However, in practice, four rods are usually placed in a straight line at intervals a , driven to a depth not exceeding $0.1 a$. Then we assume $b = 0$ and the formula becomes:

$$\rho = 2\pi a R \quad (3)$$

and gives approximately the average resistivity of the soil to the depth a .

A set of readings taken with various probe spacings gives a set of resistivities which, when plotted against spacing, indicates whether there are distinct layers of different soil or rock and gives an idea of their respective resistivities and depth. (See Fig 2.)

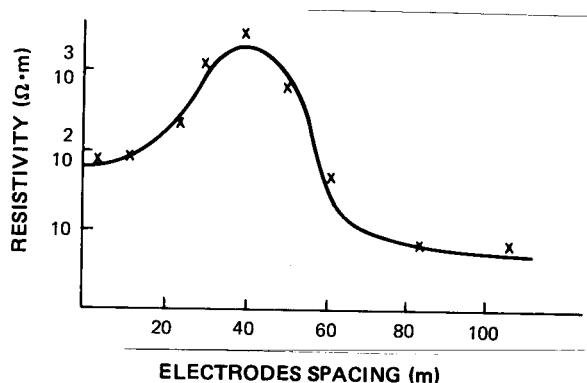


Figure 2—Typical Resistivity Curve

- 2) *Unequally-spaced or Schlumberger-Palmer Arrangement.* One shortcoming of the Wenner method is the rapid decrease in magnitude of potential between the two inner electrodes when their spacing is increased to relatively large values. Often the commercial instruments are inadequate for measuring such low potential values. In order to be able to measure resistivities with large spacings between the current electrodes the arrangement shown in Fig 3(b) can be used successfully. The potential probes are brought nearer the corresponding current electrodes. This increases the potential value measured. The formula to be used in this case can be easily determined [B35]. If the depth of burial of the electrodes b is small compared to their separation d and c , then the measured resistivity can be calculated as follows:

$$\rho = \pi c(c + d)R/d \quad (4)$$