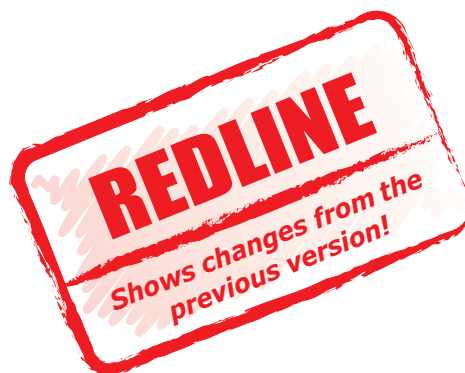


IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System

IEEE Power and Energy Society

Sponsored by the
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USA

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

Sponsor

Substations Committee
of the
IEEE Power and Energy Society

Approved 5 December 2012

IEEE-SA Standards Board

Abstract: Practical test methods and techniques are presented for measuring the electrical characteristics of grounding systems. Topics addressed include safety considerations, measuring earth resistivity, measuring the power system frequency resistance or impedance of the ground system to remote earth, measuring the transient or surge impedance of the ground system to remote earth, measuring step and touch voltages, verifying the integrity of the grounding system, reviewing common methods for performing ground testing, reviewing instrumentation characteristics and limitations, and reviewing various factors that can distort test measurements.

Keywords: electrical measurements, ground impedance, ground potential rise, ground resistance, ground testing, IEEE 81™, remote earth, soil resistivity

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Introduction

This introduction is not part of IEEE Std 81-2012, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System.

IEEE Std 81TM-1983 [B36]^a was prepared by the Power System Instrumentation and Measurement Committee of the IEEE Power and Energy Society. The guide was intended to cover the majority of field measurements that did not require special, high-precision equipment and did not address unusual difficulties that can occur in large grounding systems, abnormally high stray alternating currents (ac) or direct currents (dc), and so on. In 1991, IEEE Std 81 was reaffirmed and IEEE Std 81.2-1991 [B37] was released to cover the measurement of very low impedances (less than 1 ohm) along with specialized instrumentation, measurement techniques, and safety considerations.

After nearly two decades of inactivity, the Substation Committee of the IEEE Power and Energy Society determined that IEEE Std 81-1983 and IEEE Std 81.2-1991 contained subject matter that is very relevant for applications in electric utility facilities, but the standards needed to be updated. A working group was formed to combine both standards into a singular document that included updated instrumentation, techniques, and information. This document represents the efforts of that working group.

^a The numbers in brackets correspond to those of the bibliography in Annex F.

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IEEE Guide for Measuring Earth

Resistivity, Ground Impedance, and Earth ~~Surface~~Surface Potentials of a ~~Ground~~Grounding System

~~Part I Normal Measurements~~

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1. Overview

1.1 Scope

The test methods and techniques used to measure the electrical characteristics of the grounding system include the following topics:

- a) Establishing safe testing conditions
- b) Measuring earth resistivity
- c) Measuring the power system frequency resistance or impedance of the ground system to remote earth

- d) Measuring the transient (surge) impedance of the ground system to remote earth
- e) Measuring step and touch voltages
- f) Verifying the integrity of the grounding system
- g) Reviewing common methods and procedures for performing ground testing
- h) Reviewing instrumentation characteristics and limitations
- i) Reviewing various factors that can distort test 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.~~

The purpose of this guide is to present practical instrumentation methods that may be used for measuring soil resistivity the impedance to remote earth, step and touch voltages, and current distributions in ground grids associated with electric utility facilities. These grids typically consist of interconnected grounding systems ranging in complexity from a few ground rods to large grids with many ground rods or wells, buried conductors, and external ground connections. External ground connections may include overhead shield/ground/neutral wires, underground cable sheaths/neutrals, counterpoises, grid tie conductors, metallic pipes, and other connections that

[provide additional paths to remote earth.](#)

[This guide is intended to assist the engineer or technician in obtaining and interpreting accurate, reliable data. The factors that influence the choice of instruments are discussed along with a presentation of field techniques for various types of measurements. These factors include the purpose of the measurement, the accuracy required, the types of instruments available, the possible sources of error, and the nature of the ground or grounding system under test. It also describes test procedures that promote the safety of personnel and property, and it seeks to minimize operating interferences with neighboring facilities.](#)

2. Normative references

[The following referenced document is indispensable for the application of this document \(i.e., it must be understood and used, so each referenced document is cited in text and its relationship to this document is explained\). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document \(including any amendments or corrigenda\) applies.](#)

[IEEE Std 80TM, IEEE Guide for Safety in AC Substation Grounding.^{1,2}](#)

~~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~~

3. 4-Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards*

Dictionary Online should be consulted for terms not defined in this clause.³

~~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.~~

apparent soil resistivity: The equivalent, overall resistivity of a volume of soil with varying properties.

bonding: The electrical interconnecting of conductive parts, designed to maintain a common electrical potential.

counterpoise (overhead lines) (lightning protection): A conductor or system of conductors, typically arranged beneath a transmission or distribution line, located most frequently below the surface of the earth and connected to the grounding system of towers or poles supporting the line.

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

electric potential difference: The potential energy per unit charge between two points in an electric field.

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

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~~

ground current: A current flowing into or out of the earth or its equivalent serving as a ground.

ground electrode: A conductor embedded in the earth and used for collecting ground current from or dissipating ground current into the earth.

ground grid: A system of interconnected ground electrodes arranged in a pattern over a specified area and buried below the surface of the earth.

ground impedance: The vector sum of resistance and reactance between a ground electrode, grid or system and remote earth.

ground potential rise (GPR): The maximum electrical potential that a ground electrode, grid, or system might attain relative to a distant grounding point assumed to be at the potential of remote earth.

NOTE—Under normal conditions, the grounded electrical equipment operates at near zero ground potential. That is, the potential of a grounded neutral conductor is nearly identical to the potential of remote earth. During a ground fault the portion of fault current that is conducted by the ground grid into the earth causes the rise of the grid potential with respect to remote earth.⁴

ground resistance: The impedance, excluding reactance, between a ground electrode, grid or system and remote earth. Note that some sections of this guide refer to ground impedance as ground resistance if the reactive portion of the impedance is deemed negligible.

ground return circuit: A circuit in which the earth or an equivalent conducting body is used to complete the circuit and allow current circulation to or from its current source.

grounded: A system, circuit, or apparatus provided with a ground(s) for the purposes of establishing a ground return circuit and for maintaining its potential at approximately the potential of earth.

grounding system: Comprises all interconnected grounding ~~connections~~ facilities 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.~~

mutual resistance of grounding electrodes: Equal to the voltage change in one electrode produced by a change of current in another electrode and is expressed in ohms.

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

remote earth: A theoretical concept that refers to a ground electrode of zero impedance placed an infinite distance away from the ground under test. In practice, remote earth is approached when the mutual resistance between the ground under test and the test electrode becomes negligible. Remote earth is normally considered to be at zero potential.

soil (earth) resistivity: A measure of how much a volume of soil will resist an electric current and is usually expressed in ohm-meters.

step voltage: The difference in surface potential that could be experienced by a person bridging a distance of 1 meter with the feet without contacting any grounded object.

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.~~

touch voltage: The potential difference between the ground potential rise (GPR) of a grounding grid or system and the surface potential where a person could be standing while at the same time having a hand in contact with a grounded structure or object. Touch voltage measurements can be “open circuit” (without the equivalent body resistance included in the measurement circuit) or “closed circuit” (with the equivalent body resistance included in the measurement circuit).

transferred voltage: A special case of touch voltage where a voltage is transferred into or out of the vicinity of a ground electrode from or to a remote point external to the ground electrode.

4. Test objectives

4.1 Earth resistivity measurements

Earth resistivity measurements are used to perform the following:

- a) Estimate the ground impedance of a grounding system
- b) Estimate potential gradients including step and touch voltages
- c) Compute the inductive coupling between neighboring power and communication circuits
- d) Design cathodic protection systems
- e) Design alternating current (ac) mitigation for coupling between transmission lines and pipelines
- f) Conduct geological surveys

4.2 Impedance and potential gradient measurements

Measurement of ground resistance or impedance and potential gradients on the surface of the earth due to ground currents are used to perform the following:

- a) Verify the adequacy of a new grounding system
- b) Detect changes in an existing grounding system
- c) Identify hazardous step and touch voltages
- d) Determine GPR to design protection for power and communication circuits

⁴ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

5. Safety precautions while making ground tests

5.1 ~~Station~~-Ground ~~Tests~~electrode tests

WARNING

A lethal voltage can exist between the ground electrode under test and a remote ground.

~~It should be strongly impressed on all test personnel that a~~ A lethal ~~potential~~voltage can exist between the ~~station~~-ground electrode under test and a remote ground during routine conditions or if a power-system fault involving the station ground occurs while ground tests are being ~~made~~conducted. The ground potential rise can be in the order of several thousand volts. Step and touch voltages around the ground electrode under test, test equipment, and remote grounds can also be lethal.

A test plan is typically developed and reviewed with applicable test personnel. Appropriate safety rules need to be followed.

~~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~~are treated as though a possible ~~potential~~voltage could exist between the 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 Ω to 0.5 Ω . 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.~~

Since the are located at points that represent remote earth, The main area of concern involves system faults or lightning strikes, which can cause voltages as high as several thousand volts to occur between station ground and remote points. It is also important to understand that the test signal

injected into a remote current electrode can also result in significant touch voltages. The following precautions can reduce these hazards although other precautions might also be necessary:

a) Hands or other parts of the body be are not allowed to complete the circuit between points of possible high potential difference. Gloves and dielectrically rated footwear can reduce the hazards associated with handling test leads that extend outside the station ground grid.

b) Exposed test leads and electrodes are isolated from workers and the general public prior to applying test voltages. Exposed test leads and electrodes are also isolated from workers and the public prior to connecting the leads to a station ground grid or other grounding systems that might be exposed to system ground fault currents.

c) A signal is applied for short test periods, and all test leads are promptly removed after the test is completed.

d) If remote current and potential probes are not within sight of test personnel or if the test leads are located in an area accessible to the public, then these points are under continuous observation using a spotter in radio contact with the test equipment operator as long as the test signal is applied or remote potentials are over 50 V. One or more test leads that are electrically connected to a ground grid can cause a transfer of potential under fault conditions that would far exceed 50 V, and a spotter would be necessary as long as the test leads are connected to the ground grid.

e) If the ungrounded ends of test leads parallel an energized line for several hundred feet, then a hazardous voltage can be induced into the test leads if large currents are flowing in the energized line. This issue can sometimes be mitigated by the physical orientation of test leads, grounding, or both.

~~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 Arrester 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.

5.2 Surge arrester ground continuity tests

Surge arrester ground continuity tests require special care for the following reasons:

a) The base of the surge arrester can approach line potential if the ground lead is disconnected while the primary terminal remains energized. Never disconnect the ground of a

surge arrester for any reason while the primary terminal remains connected to an energized line.

b) Extremely high, short-duration lightning or switching currents can be discharged into the ground and can exceed 50 000 A.

c) A system fault can occur if a surge arrester fails during testing. Surge-arrester ground leads can be tested as long as sufficient safety precautions are implemented.

5.3 Neutral and shield wire ground tests

Disconnecting neutral and shield wires can generate hazardous voltages. This hazard can occur whether the line is energized or not, due to current flow through the interconnected shield wires, or mutual coupling with other energized circuits. Appropriate work procedures can mitigate these hazards.

5.4 Equipment neutral ground test

High voltages can occur and possibly harm personnel and/or damage equipment, if neutrals are disconnected from energized equipment.

6. General considerations on the problems related to measurement

6.1 Complexities

The measurements of ~~earth-soil~~ resistivities, ground impedances, and potential gradients of the earth 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~~choosing a suitable ~~direction~~pattern or locations for test probes to make a resistance test. ~~Moreover, the~~ is becoming increasingly difficult. The connection of overhead ground

wires, buried water pipes, cable sheaths, ~~etc,~~[adjacent railroad tracks, conveyor systems, and so on,](#)
[can](#) all have ~~the~~[an](#) effect ~~of physically distorting and enlarging the ground grid.~~

~~NOTE—Overhead~~[on the electrical circuit being tested and can introduce significant errors. It](#)
[should also be noted that overhead](#) ground wires ~~may~~[might](#) be insulated either deliberately or by
~~clamp corrosion~~[poor connections,](#) and therefore, low-voltage tests ~~may~~[might](#) give answers different
from actual fault tests.

~~Ground impedance measurements should be made immediately after the~~[To improve the](#)
[accuracy of the measurement for comparison with calculated values, ground impedance](#)
[measurements can be performed prior to interconnection of external shield wires, metallic pipes,](#)
[and other external interferences.](#)

~~The impedance of a~~ 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 [slightly](#) as the
earth settles to a uniform compactness ~~perhaps~~ a year [or more](#) after installation.

6.2 Test electrodes

~~The~~[Several](#) ground-impedance measurement methods described in ~~the following sections~~[Clause 7](#)
[through Clause 12](#) 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~~

[The impedance of the test electrodes can have a significant effect on the accuracy of impedance](#)

measurements. If a ground test is performed using the two-point test method, the measurement error can be minimized if the impedance of the test electrode is negligible with respect to the ground being tested. Conversely, for the three-point test method, the measurement error can be minimized if the impedance of the test electrode is similar in magnitude to the impedance of the ground under test.

Obviously, these restrictions limit the use of such methods to grounds of relatively small extent such as residential swimming pools, pole grounds, 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~~ as 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~~

Test instruments need sufficient current flowing in the test circuit to obtain accurate test measurements and reliable test results. An awareness of the test circuit is therefore necessary because it is possible for the test equipment to produce insufficient test current if the resistance of the test electrode is too high. Insufficient test current is defined as follows:

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

In case ~~(1a)~~, 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 of the electrodes involved in the current circuit. Increasing the power

supply voltage ~~is~~might not ~~always possible especially with hand-driven generators incorporated~~be an option due to limitations in the measuring instrument. ~~If an instrument.~~When this solution is practical with higher voltage is used, care must be taken to avoid dangerous potentials ~~of~~on 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~~Most test instruments supply a voltage of 50 V or less.

WARNING

If the test voltage exceeds 50 V, there is a shock hazard if anyone touches an energized conductor. Appropriate personnel protective equipment is typically used by test personnel and adequate measures implemented to protect the public from being exposed to a potentially hazardous situation.

Often, the most effective way of increasing the test current is to decrease the current electrode resistance. ~~This~~The resistance of the test electrode can be ~~done~~reduced 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. If a current electrode is made up of parallel ground rods, then adequate spacing (not closer than the below-grade length of the current electrode) between the ground rods will minimize the impact of mutual resistances.

The maximum resistance values of the current and potential electrodes will depend on the type of instrument used.

If stray currents are present when direct current (dc) tests are being performed, the interference can be mitigated by setting the test current to a value significantly above the stray dc earth currents. When tests with ac or periodically reversed dc signals are being performed, the interference can be mitigated by setting the frequency of the test signal to a frequency not present in the stray currents or use a random noise signal.

A potential probe with high resistance to remote earth can also influence the voltage measured by

the instrument. If this resistance is of the same order of magnitude as the input impedance of the instrument, then the actual voltage will be divided between the measured voltage and the voltage across the resistance of the potential electrode. In cases with low soil resistivities, the error caused by this influence is insignificant, but in the case of sandy or rocky soil environment, the user might consider reducing the resistance of the electrode to reduce this error. Otherwise, if this influence prevails, then the indicated resistance will be less than the actual resistance.

~~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~~reactions and ~~polarization~~ potential differences. Direct potentials are produced between various types of soil and between soil and metal by galvanic action. Cathodic protection systems of pipelines, dc railroad tracks, and dc transmission lines are some of the major sources of dc currents in the soil. Galvanic potentials, polarization, and, ~~if present~~, stray direct currents ~~may~~can 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~~might not be accurate for alternating-current applications. ~~Caution must be exercised in areas subject to solar-induced currents (quasi-dc)~~Solar-induced currents, which can be quasi-dc, might influence test results.

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~~can be mitigated in ground resistance measurements by utilizing a frequency that is not present in the stray current or by using a random noise signal. Most measuring devices use frequencies within a range of 50 Hz to ~~100~~3400 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 can be ~~extremely~~ low (~~for example, 0.010 Ω~~)less than 1 Ω , but it ~~may~~could have a significant ~~quadrature~~reactive component ~~[B23]¹~~(Harrison [B34]⁵). Certain precautions ~~should be taken~~are necessary when measuring the ~~60~~power frequency (usually either 50 Hz or 60 Hz) impedance of a large grounding system. For such measurements, ~~the test device should be~~devices are operated at ~~an approximate system frequency of 60 Hz, but the a~~ test frequency ~~should be~~that is slightly above or below ~~60 Hz, using a minimum of 50 A for the most~~the power system frequency to obtain more 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 Inductive~~ coupling can occur between components of two or more ac circuits by means of the mutual inductance that associates the two circuits. The coupling effect between 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~~added to the ~~desired-measured-true~~ voltage and produces a measurement error. ~~Since the~~The 50 Hz or 60 Hz inductive coupling between two parallel test leads ~~may~~might be as high as $0.1 \Omega/100 \text{ m}$. As a result, the error can be appreciable. ~~Low~~because low ground impedance usually ~~is found with a large area occurs in~~ ground, ~~which requires grids that cover large areas, and~~ long test leads are typically required to reach remote earth. Thus, the coupling between test leads can introduce large errors when a ground grid covering a large area has a relatively low impedance.

Conversely, a ~~small-area~~ ground grid that covers a small area usually has ~~fairly~~a relatively high ground impedance ~~and requires,~~ which allows 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~~ that are 10Ω or greater, is almost always important on measurements of 1Ω or less, and ~~should be considered~~can be significant in the range between 1Ω and 10Ω .

Test lead coupling ~~may~~can 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.~~ When test lead coupling is anticipated, appropriate routing may include separating the leads or crossing the leads at 90° .

6.7 Buried metallic objects

Partially or completely buried objects, such as rails, ~~water, or other industrial~~ and metallic ~~pipes~~pipelines, located in the vicinity of the ground being tested, will ~~considerably~~have considerable influence ~~the measurement on test~~ 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~~[\(Dawalibi](#) ~~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.~~[Mukhedkar \[B23\], Rudenberg \[B55\]\)](#). Earth potential contours are distorted and gradients are increased when measured above buried metallic objects.

Whenever the presence of buried metallic structures is suspected in the area where soil resistivity measurements are to be ~~taken~~[performed](#) 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~~[Locate](#) test probes ~~should be~~ as far as possible from ~~the~~ buried structures.

~~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.~~

7. Earth resistivity

7.1 General

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

Earth resistivity varies not only with the type of soil but also with temperature, moisture,

~~salt~~mineral content, and compactness (~~see Fig~~Figure 1). The literature indicates that the values of earth resistivity vary from ~~0.01 to~~less than $1 \phi \Omega$ m for sea water ~~and~~ up to $10^9 \phi \Omega$ m for sandstone. The resistivity of the earth increases slowly with decreasing temperatures from $25 \phi C$ to $0 \phi C$. Below $0 \phi C$, the resistivity increases rapidly. In frozen soil, as in the surface layer of soil in winter, the resistivity ~~may~~can 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]~~IEEE Std 80⁶ (Rudenberg [B55], Thug [B60]).

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

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

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

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]~~(IEEE Std 80, Dawalibi and Mukhedkar [B21], Endrenyi [B26], Giao and Sarma [B30], Sunde [B57], Thug [B60]) and an exponential earth ~~[B38], [B42]~~(Sunde [B57], Thug [B60]) have ~~proved~~proven to be good approximations that can be useful in determining system designs.

Some publications ~~[B9], [B10], [B18], [B20], [B31], [B36], [B38], [B39], [B42]~~(IEEE Std 80, Dawalibi

[and Mukhedkar \[B23\], Dawalibi and Mukhedkar \[B21\], Endrenyi \[B26\], Gao and Sarma \[B30\], Rudenberg \[B55\], Sunde \[B57\], Thapar and Gross \[B59\], Thug \[B60\]](#) 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—~~ [. In this case, deep soil resistivity refers to depths roughly the diameter of a horizontal electrode system or up to ten times the depth of vertical electrodes.](#) This [definition of deep soil resistivity](#) 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.~~ ⁶ [Information on references can be found in Clause 2.](#)

~~The above statements are good arguments in favor of methods which include both surface and deep soft 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.~~

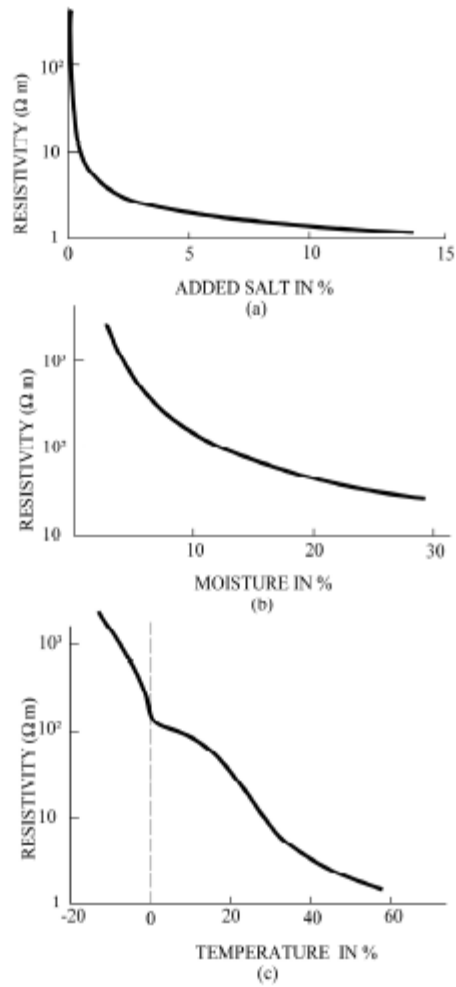


Figure 1 —Earth resistivity variations (Rudenberg [B55]):
(a) salt, (b) moisture, and (c) temperature

Table 1—Geological period and formation [B57]

Earth resistivity ohm-meters	Quaternary	Cretaceous tertiary quaternary	Carboniferous triassic	Cambrian Ordovician Devonian	Precambrian and combination with Cambrian
1 Sea water		Loam Clay Chalk	Chalk Trap Diabase Shale Limestone Sandstone	Shale Limestone Sandstone Dolomite	Sandstone Quartzite Slate Granite Gneisses
10 Unusually low					
30 Very low					
100 Low					
300 Medium					
1000 High					
3000 Very high	Coarse sand and gravel in surface layers				
10 000 Unusually high					

~~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

- [Type of soil in each layer](#)
- [Moisture content](#)
- [Soil pH](#)
- [Depth of groundwater](#)

The determination of ~~soft~~[soil](#) resistivity from the values of resistance measured between opposite faces of a soil sample of known dimensions is not recommended ~~since~~, [as](#) the unknown interfacial resistances of the soil sample and the electrodes are included in the measured value.

[Obtaining a useful approximation of soil resistivity from resistivity measurements on samples is difficult, and in some cases impossible. 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.](#)

Often, at the site where a grounding system is to be installed, extensive ~~civil engineering~~[geotechnical](#) work ~~must be carried out~~[will be performed](#). This work usually involves geological prospecting, which ~~results in~~[can provide](#) a considerable amount of information on the nature and configuration of the ~~site~~[soft soil](#). Such data could be of considerable ~~help~~[assistance](#) to the ~~electrical design~~ engineer, who should try to obtain ~~this~~[at least the following](#) information:

~~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.~~

~~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 ~~or three-point method~~

In this method, the ground resistance measurements are repeated several times in correlation with the ground rod incremental increase in depth. ~~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.~~

~~1a)~~ The theoretical value of ground rod resistance is simple to calculate with adequate accuracy, ~~therefore, the results are easy to interpret.~~

b) Driving ground rods also gives confirmation of how deep the rods can be driven during installation.

~~2) — The driving of a rod into the soil is normally an easy operation.~~

A disadvantage of this method is that the rod might vibrate as it is driven, resulting in poor contact with the soil along its length, thus, making a conversion to true apparent resistivity difficult.

The variation of depth method gives useful information about the nature of soil in the vicinity of the rod (~~5~~five to ~~10~~ten times the rod length). For additional details regarding this method, refer to 8.2. For large areas, several rod locations can give an indication of significant lateral changes in soil resistivity. If a large volume ~~of soil must be investigated,~~ (large area and depth) of soil is tested, then it is might be preferable to use the four-point method, ~~since the~~ because driving ~~of~~ long rods ~~is~~ might not be practical in some soils.

~~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~~ apparent resistivity ~~at increased~~ for each depth. ~~Usually of the tested electrode is a rod. Rods~~ Ground rods are preferred ~~to other types of electrodes for this measurement~~ because they offer two important advantages:

~~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.

7.2.3 ~~Two~~ Four-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 . 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.~~

A good method in practice for measuring the average apparent resistivity of large volumes of undisturbed earth is the four point method [B43]. Small electrodes(Wenner [B62]). Four auxiliary probes are buried in four small holes installed 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, the V/I ratio gives the resistance R in ohms.

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

a) *Equally Spaced or Wenner Arrangement.* With this arrangement, the probes are equally spaced, as shown in Figure 2(a). Let a be the distance between two adjacent probes. Then, the apparent resistivity ρ in the terms of the length units in which a and b are measured is

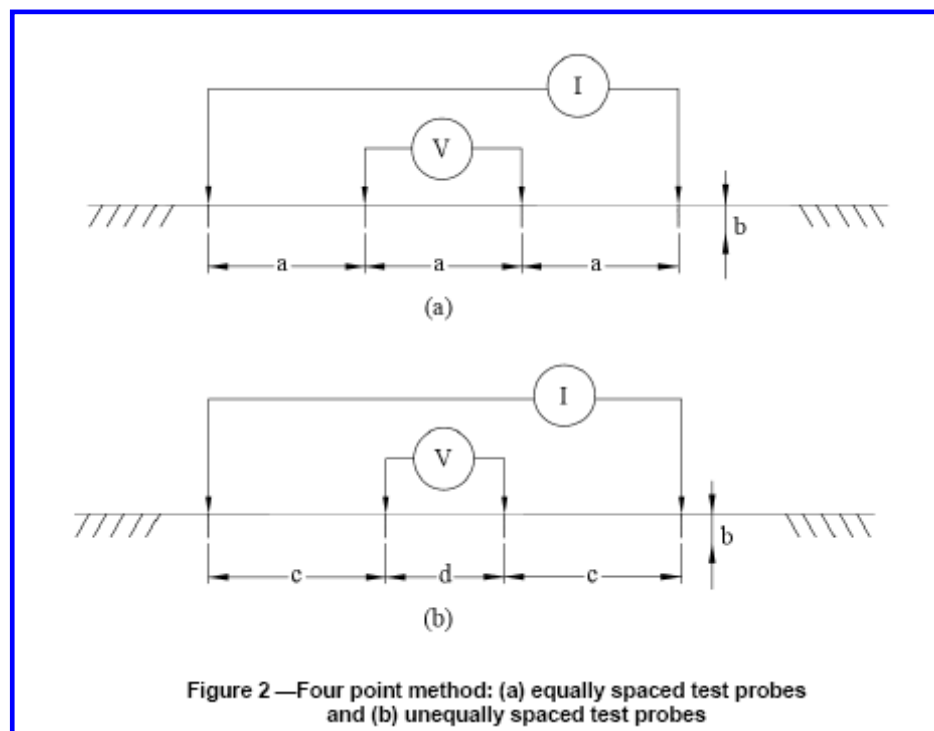
$$\rho = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \quad (2)$$

Theoretically, the electrodes should be point contacts or hemispherical electrodes of radius b . 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, the user can assume $b = 0$ and the equation 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 that, 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 (Figure 3).



[\(New\)](#)

b) *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~~ Historically, instruments ~~are~~ were inadequate for measuring such low potential values. ~~In order to be able~~, although improved sensitivity in modern testers mitigates this disadvantage to ~~measure resistivities with large spacings between the current electrodes the~~ some extent. Another disadvantage with the Wenner method is the requirement to reposition all four probes for each depth to be measured. The arrangement shown in ~~Fig 3~~ Figure 2(b) can be used to measure soil resistivity successfully. ~~The potential when current probes are brought nearer the corresponding~~ separated by a large distance or to expedite testing for multiple current ~~electrodes. This increases the potential value measured~~ probe locations.

With the Schlumberger method, the inner probes are placed closer together and the outer probes are placed farther apart. Unlike the Wenner method, which requires all probes to be moved to calculate soil resistivity at different depths, the Schlumberger method only required the outer probes to be repositioned for subsequent measurements. Reducing the number of probes to be repositioned for each test makes the Schlumberger method a faster choice for testing at different depths.

The ~~formula~~ equation to be used in this case can be easily determined ~~[B35]~~ (Palmer [B50]). If the depth of burial of the electrodes b is small compared to their separation d and c , and $c > 2d$, then the measured apparent resistivity can be calculated as follows:

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

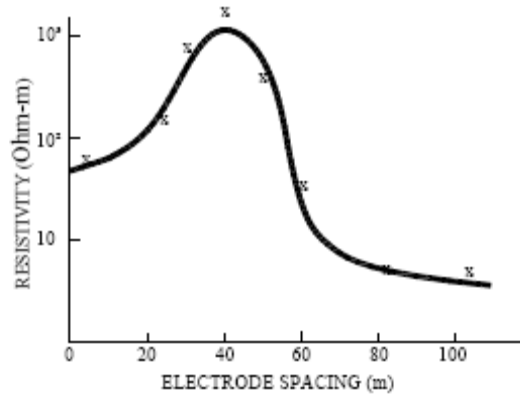


Figure 3 —Typical resistivity curve

Like the variation of depth method, the four-point method gives the apparent resistivity for a specific, although broader, volume of soil. It is advantageous to take measurements along several profiles around the area of concern to detect lateral changes in soil resistivity, as well as to determine any possible interference effects on the measurements due to nearby conductive objects. Another way to gain confidence that conductive objects in the earth do not affect the measurements is to repeat the same measurement in the same location, but 90° relative to the first one. The measured values should correlate.

7.3 Interpretation of measurements

The interpretation of the results obtained in the field is perhaps the most difficult part of the measurement process. As mentioned in 7.1, the earth resistivity variation is large and complex because of the heterogeneity of earth. Except for very few cases, it is essential to establish a simple equivalent to the earth structure. This equivalent depends on the following factors:

- 1 a) The accuracy and extent of the measurements
- 2 b) The method used
- 3 c) The complexity of the mathematics involved
- 4 d) The purpose of the measurements

For applications in power engineering, the two-layer equivalent model is accurate enough [in many cases](#) without being mathematically too involved. [However, there are computer solutions available that can effectively estimate multilayer soil models for various measurement techniques.](#)

7.3.1 Geological information and soil samples

Special tools or mathematical equations are not necessary to interpret such information, which are mainly given in the figures and tables provided by geological explorations.

[As shown in Table 1, determining an accurate soil model from simple classifications of types of soil is difficult. The classifications simply give a crude estimation of the resistivity of different types of soils.](#)

7.3.2 Variation of depth method (see ~~Appendix~~ [Annex B](#))

The following interpretations assume that the tested ground is a rod driven ~~at depth l . The~~ [to various depths \$l_1\$ through \$l_n\$.](#) Table 2 shows a sample set of measured values. Assuming the rod radius r is small compared to l . ~~For other forms of electrodes the calculations will,~~ [Equation \(7\) can be ~~similar to the following~~ used to compute an apparent resistivity for each measured value. The user should note that Equation \(7\) is derived based on the assumption of uniform soil resistivity, so the apparent resistivity is approximate, at best.](#)

The ground resistance of the rod buried in a uniform soil is given by ~~reference [B39]~~ [Thug \[B60\]](#):

$$R = \frac{\rho}{2\pi l} \ln \frac{2l}{r} \quad (5)$$

or

$$R = \frac{\rho}{2\pi l} \ln \left(\frac{4l}{r} - 1 \right) \quad (6)$$

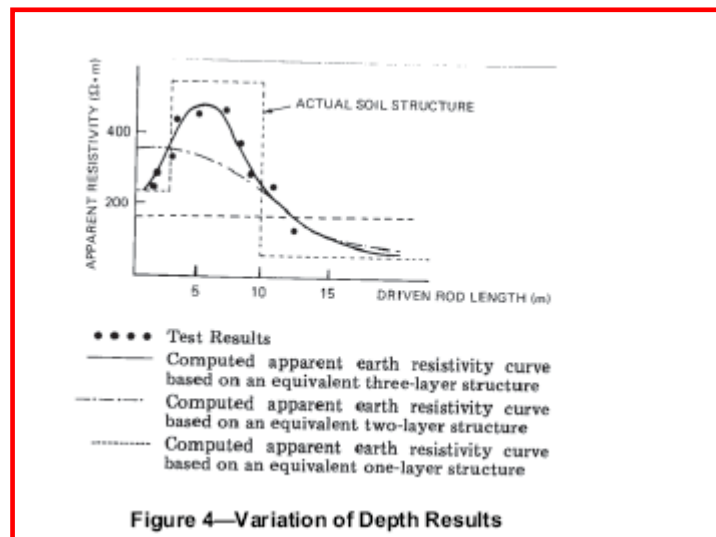
depending on the approximations used.

[Rearranging for apparent resistivity gives:](#)

$$\rho_a = \frac{R2\pi l}{\ln\left(\frac{4l}{r}\right) - 1} \quad (7)$$

For each length l of the rod, the measured resistance value R determines the apparent resistivity value ρ_a which, when plotted against l , provides a visual aid for determining earth resistivity variation with depth. For more clarity, suppose that the field tests of Table 2 gave the curve shown in Figure 4(a) and Figure 4(b). These curves were mathematically derived to fit perfect two-layer soil models. By inspection of the curve, it can be concluded that the soil structure for Figure 4(a) is at least two distinct layers. For small values of l (0 m to 6 m), the soil has a resistivity value of nearly 300 Ω -m. The lower layer is more conductive. Its resistivity value approaches 100 Ω -m. Thus, an adequate two-layer soil model can be obtained by visual inspection for this case. Now consider the curve of Figure 4(b). For this case, the upper layer soil is approximately 100 Ω -m to a depth of approximately 6 m. However, the exact value of the lower layer cannot be obtained through visual inspection. The value appears to approach 250 Ω -m, but the correct value is 300 Ω -m. The following two solutions are then possible:

- 1 a) Continue measurements with rods driven deeper into the soil
- 2 b) Use analytical techniques to compute, from the measured data, an equivalent earth resistivity model-~~structure~~



(Deleted)

Table 2—Expected three-point field measurements for mathematically derived two-layer soil models

Rod depth m (ft)	$\rho_1 = 300, \rho_2 = 100, h = 6.1 \text{ m (20 ft)}$		$\rho_1 = 100, \rho_2 = 300, h = 6.1 \text{ m (20 ft)}$	
	Resistance (Ω)	Apparent resistivity ($\Omega\text{-m}$)	Resistance (Ω)	Apparent resistivity ($\Omega\text{-m}$)
0.3 (1.0)	647.60	299.3	218.30	100.9
0.9 (3.0)	270.60	296.5	92.68	101.6
1.5 (5.0)	177.10	294.7	61.52	102.4
3.0 (10.0)	97.63	290.0	35.13	104.4
4.5 (15.0)	67.85	284.5	25.43	106.6
6.1 (20.0)	50.82	272.6	20.63	110.7
9.1 (30.0)	21.77	165.8	18.22	138.7
15.2 (50.0)	10.91	129.7	14.58	173.3
21.3 (70.0)	7.41	118.4	12.16	194.2
27.4 (90.0)	5.64	112.5	10.42	207.8
33.5 (110.0)	4.57	108.9	9.13	217.5
39.6 (130.0)	3.84	106.1	8.12	224.3
45.7 (150.0)	3.32	104.2	7.31	229.4

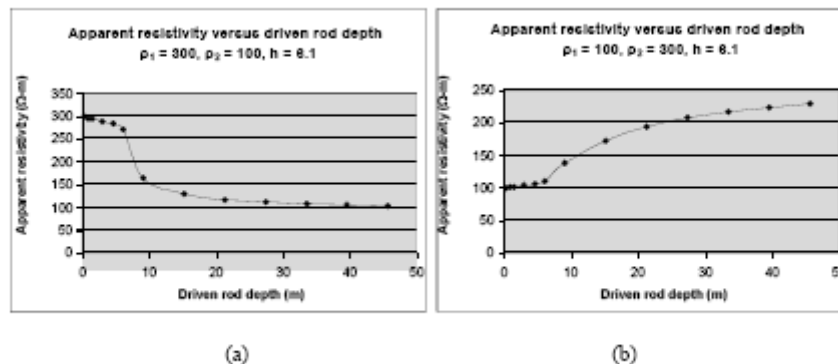


Figure 4—Variation of depth mathematically derived field measurements

(New)

When using analytical methods (computer software) to determine the soil parameters, it is appropriate to replace the simple Equation (5) or Equation (6), which assume uniform soil resistivity, with more exact equations based on layered soil models. Then, the soil parameters for each layer can be determined to obtain the best fit with the measured driven-rod resistances.

Additional measurements will certainly help in obtaining the resistivity of each layer. However, the thicknesses of each layer are not always easy to determine. Moreover, driving rods to great depth can be difficult and expensive. ~~Other alternatives consist of assuming earth as uniform, two-layer structured (or more), and being composed of a material whose resistivity varies with depth according to a simple mathematical law (linear, exponential...).~~