



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

IEEE Power and Energy Society

Developed by the
Substations Committee

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

Developed by the

Substations Committee
of the
IEEE Power and Energy Society

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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 touch and step 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 81-2025, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System.

This edition of IEEE Std 81 has been updated to include both new and existing methods for assessing grounding performance of ground grids. The main clauses have been restructured to clarify the context and scope of each method. The guide now features current injection testing (CIT) methods, offering practical solutions for evaluating both new and existing sites.

All test methods in the guide have been revised and updated to reflect the latest industry standards. The Working Group established a task force, which authored technical report PES-TR-107 [B64]⁶ on surface aggregate testing. Key findings and recommendations from this report have been integrated into the guide.

Initially, IEEE Std 81™-1983 [B55] was prepared by the Power System Instrumentation and Measurement Committee of the IEEE Power and Energy Society. The guide was intended to cover most 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 [B56] was released to cover the measurement of very low impedances (less than 1 Ω) along with specialized instrumentation, measurement techniques, and safety considerations.

In 2010, after nearly two decades of inactivity, the Substation Committee of the IEEE Power and Energy Society determined that IEEE Std 81-1983 [B55] and IEEE Std 81.2-1991 [B56] contained subject matter that is very relevant for applications in electric utility facilities, but the standards needed to be updated. IEEE Std 81™-2012 was released to combine both standards into a singular document that included updated instrumentation, techniques, and information. Much of the content in the 1991 part 2 of the guide involved detailed instrumentation and other practical advice for testing large grounding systems that may still be relevant for use today. Throughout the current revision of the guide, it was identified that some of the previous content in the second part of the guide might be helpful with revisions in future versions of the guide.

In 2017, the Working Group conducted an industry survey on grounding practices and gathered feedback from end users of the guide regarding the test methods they employed and their assessment approaches, which initiated the development of this revision of the guide.

Acknowledgments

IEEE Copyright Permission via Rights Link to use Figure 32—Test setup for determining soil frequency response in Visacro S., Alipio R., Murta Vale M. H., and Pereira C., “The response of grounding electrodes to lightning currents: The effect of frequency-dependent soil resistivity and permittivity,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 53, no. 2, pp. 401–406, May 2011.

⁶ The numbers in brackets correspond to those of the bibliography in Annex J.

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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:

- Establishing safe testing conditions
- Measuring earth electrical resistivity
- Measuring the power system frequency resistance or impedance of the grounding system to remote earth
- Measuring the transient (surge) impedance of the grounding system to remote earth
- Measuring step and touch voltages
- Verifying the integrity of the grounding system
- Reviewing common methods and procedures for performing ground testing
- Reviewing instrumentation characteristics and limitations
- Reviewing various factors that can distort test measurements

1.2 Purpose

This guide presents practical effective methods for measuring soil electrical resistivity and the condition and performance of grounding systems. Measurable parameters include grid resistance, grounding system impedance, ground potential rise (GPR), touch and step voltages, and current distributions in and from the system. These grounding grids and systems typically consist of interconnected grounding components 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 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 method 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.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{7,8}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they 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 80™, IEEE Guide for Safety in AC Substation Grounding.^{9,10}

3. Definitions, acronyms, and abbreviations

3.1 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.¹¹

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

bonded: *See: bonding.*

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

conductive coupling: *See: mutual ground resistance.*

⁷ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

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continuity: The ability of a system to have its components bonded altogether with a low electrical resistance.

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 via conductive, inductive, or capacitive means.

coarse aggregate: Crushed stone and other mineral materials consisting primarily of gravel sized particles greater than a No. 4 (4.75 mm) mesh screen.

current division factor: *See:split factor. Syn:fault current division factor.*

current injection test (CIT): Test in which a known current is injected into a grounding system or grounding grid in terms of determining its performance by measuring surface voltages and current through components.

current splits: The portion of electric current that flows during a fault or test condition from the ground grid through other paths than through soil.

dense graded aggregate: An aggregate with a significant amount of coarse aggregate sized particles and substantial quantity of smaller particles that fill the void spaces between the larger particles.

dry unit density: The dry weight per unit volume of material such as aggregate.

earth: *See:ground.*

earth current: *See:ground current.*

earth impedance: *See:ground impedance.*

earth potential rise (EPR): *See:ground potential rise (GPR).*

earth resistance: *See:ground resistance.*

earthed system: *Syn:grounding system.*

electric potential: The potential difference between the point and a surface that is arbitrarily chosen as having zero potential, such as remote earth.

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

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

error: **(A)**The difference between the true or actual value and the measured value. **(B)**The difference between the model and the measured value.

feeder injection: Injection circuit that consists of using a transmission line or a distribution line as a test lead to the remote electrode during CIT.

fence touch voltage: The fence touch voltage is measured between a metallic fence and the soil surface within 1 m (arm touch distance).

gate touch voltage: The gate touch voltage is the maximum potential difference between a metallic gate and the soil surface within 1 m (arm touch distance) for any position of the gate.

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. *Syn:* **earth**.

ground current: A current flowing into or out of the earth (soil) or its equivalent serving as a ground. *Syn:* **earth current**.

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.

ground electrode: A conductor embedded in the earth and used for collecting ground current from or dissipating ground current into the earth. Under this definition, a ground electrode may include counterpoise and grading conductors and concrete-encased electrodes. *Syn:* **Ufer grounds**.

ground grid: *See:* **grounding grid**.

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

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. *Syn:* **earth potential rise (EPR)**.

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.¹²

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

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.

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

grounding system: Comprises all interconnected grounding facilities in a specific area. *Syn:* **earthed system**.

inductance: A measure of the capability to oppose to the flow of a varying electrical current, measured in Henry.

induction: Generation of a voltage or current by an energized circuit on an adjacent circuit or conductive object by means of electric field coupling or magnetic field coupling.

insulated: An item that has conductive parts and is either coated or covered with a dielectric material to provide electrical insulation.

¹² Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

integrity: A measure of electrical continuity between two or more conductive items so when energized will be able to become an acceptable path for current conduction and with a negligible voltage drop across the elements and their points of interconnection.

interference: Disturbance to the normal or expected operation of electrical or electronic devices, equipment, and systems.

loaded voltage: Measured surface voltage during CIT that represents a closed-circuit touch or step voltage exposure.

loop impedance: Measured or calculated impedance (in ohms) of the current injection circuit during CIT.

master ground: A temporary protective jumper (or grounding switch) that is applied to control line accidental energization and allow for working on a de-energized circuit and that is rated to withstand full fault current.

mesh touch voltage: The mesh touch voltage is measured between the ground grid GPR and the lowest soil surface potential within the footprint of a grounding grid mesh.

mixed graded aggregates: An aggregate that generally refers to open graded aggregate mixtures that have become fouled by mineral particles such as sand, silt and clay limiting the aggregate to free drain precipitation from the aggregate.

multigrounded neutral (MGN): Multigrounded neutral system (or multi-earthed neutral system MEN in some areas) are three phase, four-wire system, where a neutral is installed and connected to ground at regular intervals along a low-voltage system. The neutral conductor is connected to the ground at distribution transformers, customer installations and at regular specified distances. For cable systems, the cable shields or concentric neutrals are grounded at any exposed location where personnel can come in contact.

mutual earth resistance (MER): The interference caused by two ground electrodes placed close to each other and connected to the soil. The interference causes a distortion of the surface scalar potentials and influences each electrode in the circuit. The closer the electrodes become, the greater the influence in the measurements of electrode resistance and surface voltages. *Syn:* **mutual ground resistance; conductive coupling.**

mutual ground resistance (MGR): *See:* **mutual earth resistance.**

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.

open graded coarse aggregate: An aggregate with a significant number of void spaces that allows water to freely drain through the aggregate. Commonly referred to as clear stone, washed stone or crushed stone. Generally, contains less than 10% of material passing the No. 4 (4.75 mm) mesh sieve.

overhead ground wire: *See:* **shield wire.**

overhead wire: *See:* **shield wire.**

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

prospective voltage: Measured surface voltage during CIT that represents an open circuit touch or step voltage exposure.

reactance (X): The nonresistive component of impedance in an ac circuit arising from the effect of inductive and/or capacitive current to be out of the phase with the emf causing it.

remote earth (RE): 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.

remote transferred touch voltage: The remote transferred touch voltage is the maximum potential difference between a remotely bonded metallic object and the soil within 1 m (arm touch distance) of the metallic object. Examples include a water faucet at a neighboring residence bonded to the multigrounded distribution neutral or a remotely grounded telephone cable sheath.

residual current (I_{res}): The resultant of the vector subtraction of the injected current and the sum of all the outgoing current paths to the ground grid.

resistance (R): A measure of the opposition to the flow of electric current by a material, measured in ohms.

resistivity (ρ): A measure of the property of a material or medium to oppose to the flow of electrical current, measured in ohm-meters.

Rogowski coil: A flexible, open ended, air cored coil, used to wrap around a conductor and measure the rate of change of current flowing through it (named after Walter Rogowski).

safety: The condition of being protected from unacceptable risk.

saturated aggregate: An aggregate with its pores completely filled with water and the surface is visibly wet.

sensitivity: The quality or condition of equipment to detect a wanted or unwanted signal.

shield wire: Metallic conductor installed on top of transmission lines between towers for the purpose of shielding the phase conductors from lightning strikes. Examples are overhead ground wires, aerial ground wires, sky wires, static wires, pilot wires, and optical ground wires (OPGWs). *Syn:* **static wire; overhead wire; overhead ground wire.**

soil layer: Portion of soil of a finite depth and thickness that has or that can be represented as a near homogeneous resistivity.

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

split factor (Sf): The ratio of the current flowing through the ground grid to the total fault current in the grounding system, often expressed as a percentage. It is also the inverse of the ratio of the asymmetrical fault current to the portion of the current that flows between the ground grid and surrounding earth. *Syn:* **current division factor.**

static wire: *See:* **shield wire.**

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

stray current: The portion of current that flows over an unintended or undesired path, often due to factors like stray capacitance between an object and surrounding structures (e.g., ground plane or walls), rather than through the intended or preferred circuit path.

structure touch voltage: The structure touch voltage is measured between a grounded structure (or metallic object inside the substation) and the soil surface within 1 m (arm touch) distance. The maximum usually occurs at structures near the edge of the grid.

station transferred touch voltage: The station transferred touch voltage is the maximum potential difference between the ground grid and the soil within 1 m (arm touch distance) of a metallic object exterior to the grid but bonded to the grid. Examples include a case-grounded power tool used beyond the grid, the sheath of bonded power cables on a riser pole, the external shutoff valve for a water supply pipe bonded to the grid, or a railway track bonded to the grid.

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

test traverse: A set of measurements of voltage over the surface on a straight line aligned with two current electrodes for the purpose of measuring soil resistivity.

touch voltage (E_t): 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”/“prospective” (without the equivalent body resistance included in the measurement circuit) or “closed circuit”/“loaded” (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.

two-electrode test vessel: A nonconductive container of known internal dimensions with two end plate electrodes for measuring the resistivity of a substance.

Ufer ground: A concrete-encased electrode, sometimes used to improve (reduce) electrical resistance to remote earth in areas with high soil resistivity.

uniform soil: Soil or layer of soil with same or very similar resistivity value.

voltage: *See:* electric potential difference.

voltage traverse: A set of consecutive surface potential measurements with respect to a reference point taken at different distance intervals on a straight line that are intended to show a pattern of a surface voltage gradient.

3.2 Acronyms and abbreviations

ac	alternating current
a	probe spacing (Wenner test), in m
A	cross-sectional area of test box, in m ²
$B(\omega)$	electrical susceptance as a function of frequency, in S
c	distance between CP and PP (Schlumberger test), in m
C1, C2	current probes
CIT	current injection test
CT	current transformer
C, CP	current probe

CSA	cross-sectional area
dc	direct current
d, D	distance between current probes, in m
DP	direct push test method
D_{sub}	length of diagonal of substation or site, in m
ϵ	electrical permittivity, in F/m
ϵ_r	relative electrical permittivity
E	(A): voltage, in V; (B): electrode of interest
E_s	step voltage, in V
E_t	touch voltage, in V
EM	electromagnetic
EMC	electromagnetic compatibility
EMF	electromotive force, in V
FACT	flexible ac transmission
FFT	fast Fourier transform
FOP	fall of potential (A): used in ground grid resistance test; B: used in voltage traverse test)
G	ground; grounding grid center
$G(\omega)$	electrical conductance as a function of frequency, in S
GPR	ground potential rise, in V
GSU	generator step-up (transformer)
h	soil layer depth, in m
HVDC	high-voltage dc transmission
I_b	body current, in A
I_g	grid current, in A
I_{res}	residual current, in A
I_{test}	test current, in A
K_{geo}	geometric constant (transient response)
l	long rod depth, in m
L	test vessel depth (aggregate), in m
μ	(A): electrical permeability, in H/m; (B): slope-variation coefficient; (C): slope-variation coefficient (slope method)
μ_r	relative electrical permeability
MER	mutual earth resistance, in Ω
MGR	mutual ground resistance, in Ω
MGN	multigrounded neutral
OHSW	overhead shield wire

OPWG	optical ground wire
$P1, P2$	potential probes
P	potential probe
PP	potential probe
PP_T	potential probe target distance (slope method)
r	rod (probe) radius, in m
RE	remote earth
RFI	radio frequency interference
rms	root mean square value
R_g	grid resistance, in Ω
R_{series}	series resistance in Ω
ρ	resistivity, in $\Omega \cdot m$
ρ	resistivity, in Ω
ρ_a	apparent resistivity, in $\Omega \cdot m$
ρ_i	resistivity of a given soil layer $\Omega \cdot m$ ($\rho_i, \dots$), in i
$\rho(\omega)$	frequency-dependent soil resistivity, in $\Omega \cdot m$
TPG	temporary protective grounding
TSO	transmission system operator
SCADA	supervisory control and data acquisition
S_f	split factor, current division factor
SSD	saturated surface dry condition (aggregates)
V	source voltage, in V
x	distance between potential probes, in m
$Y(\omega)$	electrical admittance as a function of frequency, in S
$Z(t)$	transient impedance as a function of time, in Ω
Z_g	grid impedance, in Ω
Z_{sys}	system impedance, in Ω

4. Test objectives

4.1 Overview

The objective of testing a grounding system is to determine through measurement the characteristics of the various parts of the electrical circuits that form part of or influence the performance of the grounding systems.

The detailed objectives of tests can vary depending on the stage of the grounding system life cycle. For example, if preparing for a greenfield design (i.e., site not yet built), soil electrical resistivity testing may be an appropriate test to gather data to support design assumptions. However, if the design is for development of a brownfield site (i.e., existing site), current injection testing (CIT) can be used to determine design inputs such as current splits and existing component impedances. Examples of common life cycle testing stages are provided in 9.3.

An appropriate selection of tests can significantly reduce uncertainty with respect to the performance of a grounding system. All test methods can be subject to errors, and identifying sources of error may require careful examination of the testing environment. The limitations and benefits of each test method should be understood, and the application of tests should consider the full scope of the grounding system to be tested.

4.2 Earth resistivity testing

The principal objective of earth (soil) resistivity testing is to build an understanding and a confidence of the electrical performance of the soil. Earth resistivity should not be confused with thermal resistivity or other uses of resistivity. Earth resistivity testing methods may be combined with other sources of information to create electrical models and to establish a model that is appropriate for use in analysis and decision-making. Some common uses of soil resistivity values are listed as follows:

- Estimating ground grid resistance
- Estimating potential gradients including estimating touch and step voltages
- Estimating the inductive coupling between neighboring power and communication circuits
- Modeling for the design of cathodic protection systems
- Modeling for the design of ac mitigation for coupling between transmission lines and pipelines
- Modeling for the design of lightning protection systems

4.3 Integrity testing

The main objective of integrity testing is to determine or confirm that all components and equipment that should be bonded to the ground grid are properly bonded to the ground grid, that the ground grid itself is properly bonded, and that components or equipment that should not be bonded to the ground grid are segregated.

Integrity testing can assist in answering the following questions:

- Is the ground grid properly installed and connected?
- Is the ground grid in suitable condition?
- Is every piece of equipment properly bonded?
- Are multiple connections all in suitable condition?
- Is an isolated fence still segregated?
- Is the ground grid isolated from water utilities?
- Are there any islanded grid sections (especially following site excavations)?

4.4 Resistance, impedance, and potential gradient measurements

Measurement of grounding system resistance or impedance, and potential gradients on the surface of the earth due to ground test current, are used to do the following:

- Validate the performance of a new ground grid or grounding system
- Validate the performance of an existing or aged ground grid or grounding system
- Detect changes in an existing grounding system through trends over time
- Determine the GPR
- Demonstrate earth potential contours for interference coordination (e.g., telecommunications)

4.5 Direct touch and step voltage measurement

The voltages created by the injected test current can be directly measured to do the following:

- Demonstrate compliant touch and step voltages
- Identify hazardous touch and step voltages
- Measure the potential difference between two locations to assess voltage stress

4.6 Current distribution measurement

During injection of test current, the measurement of current flowing through alternative paths can be made, which can be used to do the following:

- Validate or determine current splits (split factor S_f)
- Estimate the ground grid current I_g (see 9.5.6.7)
- Determine the contribution each current path makes, and calculate its apparent impedance
- Estimate the contribution of inductive currents by comparing phase measurements
- Identify transfer paths that require further investigation
- Identify potential transfer hazards

5. Safety precautions while performing ground tests

5.1 General safety precautions

WARNING

Serious injury may result if the following procedures are not followed when performing the tests described in the guide. In addition to usual electrical hazards, a hazardous or potentially lethal voltage can exist between the grounding system under test and any remote point.

A hazardous or potentially lethal voltage can exist or develop when performing the tests described in this guide. The source of these voltages may be the test equipment itself, steady state ground current, lightning, or a fault or other transient in the power system. Touch and step voltages around the ground electrode under test, test equipment and remote grounds can be hazardous or potentially lethal.

A test plan should be developed and reviewed with personnel. Appropriate safety procedures shall be developed and followed, and appropriate risk management controls shall be used. Industry electrical safety codes and standards such as IEEE C2® (NESC®) [B2] and NFPA 70E-2012 [B74] shall be consulted. All local, state, regional, and national regulations with jurisdiction shall be followed. For example, in the United States, 29 CFR 1910.269 [B76] applies to work on electric utility systems.

Proper consideration shall be given to test leads used during testing with respect to electric shock hazards. They should generally be treated as though a voltage could exist between test leads and any other point. A 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. These hazardous potentials can be transferred via test leads and other conductive structures to create touch and step voltage hazards. It is also important to understand the voltage produced by the test current and protect people against related potentially hazardous touch voltages.

The following precautions are a list of controls that may be used to help reduce potential hazards when performing tests described in this guide:

- a) Avoid unprotected contact between points of possible hazardous test voltage.
- b) Isolate exposed test leads and electrodes from workers and the public.
- c) Apply test voltage for short durations of time.
- d) Apply a lower test voltage.
- e) Provide supervision of test leads and probes.
- f) Provide a means to stop or reduce the test signal.
- g) Select test lead orientation and routing to help reduce electromagnetic coupling with overhead or underground energized circuits.
- h) Choose when to connect or disconnect test leads.

In the event of expected or actual lightning activity in the vicinity of field testing, work should not proceed without a risk assessment and adequate risk controls. In some cases, work should not proceed and all test leads should be disconnected.

5.2 Continuity tests to surge arresters

Exercise caution when conducting continuity tests on the grounding of surge arresters 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.
- c) A system fault can occur if a surge arrester fails during testing.

Surge arrester ground leads can be tested as long as appropriate safety precautions are implemented.

5.3 Neutral and shield wires

Disconnecting neutral and shield wires can present hazardous voltages that also possibly harm personal and/or damage equipment. 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 help reduce these hazards to acceptable levels.

5.4 Grounding bonds

High voltages can occur and could harm personnel and/or damage equipment if ground bonds are isolated, disconnected, or damaged. Generally, testing does not require the disconnection of any bonds. If it is determined that a bond must be disconnected, appropriate controls should be implemented to do so safely. Controls may include the use of insulating tools, insulating gloves, insulating matting, and dielectric footwear.

6. General considerations related to measurements

6.1 Complexities

The measurement of soil resistivity, grounding impedance, and potential gradient of the earth introduce complexities not commonly encountered in other resistance, impedance, and potential measurements. Every test lead may be coupled inductively to other current paths. This can include power system current, during normal load or fault, that can make the test signal very difficult to measure or even cause equipment damage. It can also include the test current itself. This requires consideration of whether the associated ac induction is an error to be determined and corrected or can be ignored.

Similarly, any test lead may connect to an electrode, or something else, that is at a potential other than the impressed test voltage. Unidentified buried conductive items, such as conductive pipes or poorly insulated cable armoring, can create errors by changing what is measured. Stray currents and standing voltages, both ac and dc, can present further error that must be considered, ascertained, and corrected as necessary.

In some situations, it might be necessary to perform several measurements via different means and compare results carefully to correctly determine what is in error and what measurement is reliable.

With development of residential, commercial, and industrial growth adjacent to power facilities (e.g., substations), choosing test configurations free of inductive or conductive interference may become increasingly difficult. The presence of overhead ground wires, buried water pipes, cable sheaths, railroad tracks, conveyor systems, and other conductive objects can all influence the electrical circuit being tested and can introduce significant errors. It should also be noted that overhead ground wires might be insulated either deliberately or by poor connections (with high resistance). If there is a poor connection with a voltage-dependent resistance, very-low test voltages may produce results different from what is found if a higher test voltage is used. Depending on what system is being tested, poor connection may cause an error that needs to be corrected. Testing may also identify a poor connection that needs to be remediated.

Measurements can be performed prior to interconnection of external shield wires, metallic pipes, and other external interferences, but consideration should be given to the ohmic or conductive coupling that does occur between grounding systems even when they are not directly connected by conductors. Similarly, inductive coupling should always be considered.

Complexities due to variation in surface material resistivity or compactness and terrain elevation changes along the traverse can impact the accuracy of the test results.

6.2 Test electrodes

Several measurement methods described in this guide require the use of electrodes (probes) when measuring voltage and injecting current. The impedance of the test electrodes can have a significant effect on measurement accuracy. The impedance of a test electrode refers to the impedance of the test electrode to the surrounding soil, not the self-impedance of the actual metallic electrode. For example, if a ground test is performed using the two-point test method, the measurement error can be reduced 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 reduced if the impedance of the test electrode is similar in magnitude to the impedance of the ground under test.

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 may include the following cases:

- a) Current lower than the instrument sensitivity
- b) Current in the order of magnitude of the stray current in the earth
- c) Both case a) and case b)

In case a), one corrective action available at the site of measurement is to increase test current. This can be done either by increasing the voltage of the power supply or by decreasing the resistances of the electrodes involved in the current circuit. Increasing the power supply voltage might not be an option due to limitations in the measuring instrument. If an instrument with higher voltage is used, care must be taken to avoid dangerous potentials on the electrodes and test leads.

In any of the three cases, it may be possible to use equipment more sensitive to the test current and less sensitive to the stray current.

The resistance of the test electrode can be reduced by driving the rod deeper into the soil, pouring water (with or without salt) around the rod, or driving additional rods and connecting them in parallel. Reducing the resistance of test electrodes can allow higher test current that sometimes can reduce error. However, in some scenarios, reducing the resistance of potential or current electrodes may introduce or increase errors. Care should be taken when using these techniques. 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 can reduce the impact of mutual resistance. The maximum allowable resistance values of the current and potential electrodes will depend on the type of instrument used.

A potential probe with high resistance to remote earth can 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 instrument will measure inaccurately. It will always measure only part of the actual voltage as the meter and the electrode form a voltage divider. In cases with low soil resistivity, the error caused by this influence may be insignificant, but in the case of high-resistivity soil, the user might consider reducing the resistance of the electrode to reduce this error. Otherwise, if this influence prevails, then the indicated value will be less than the actual value. This error is commonly nonconservative and can be substantial, especially in high-resistivity soils. In such cases, lowering the test electrode resistance should be considered.

6.3 Stray direct currents

Conduction of electricity in the soil is electrolytic, and direct current results in chemical reactions and potential differences. Direct potentials are produced between various types of soil and between soil and metal by galvanic action. Cathodic protection systems (e.g., of pipelines or jetties), dc railroad tracks, and dc transmission lines, wired telephone systems, and power electronics are some of the sources of dc currents in the soil. Galvanic potentials, polarization, and stray direct currents can seriously interfere with direct current measurements. Solar-induced telluric currents, which can be quasi-dc, can also influence test results. However, when using periodically reversed direct current for resistance measurements, the resulting values can be accurate but may not be a suitable value for an alternating current impedance analysis. It is common but not certain that ac tests have good immunity to dc noise.

6.4 Stray alternating currents

Stray alternating currents in the earth, in the grounding system under test, and in test electrodes present complications. The effects of stray alternating current can be mitigated in ground measurements by using an ac test frequency that is not present in the stray current or by using a range of frequencies such that the noise is a very small error. The use of filters or narrowband measuring instruments, or both, is often required

to overcome the effects of stray alternating currents. It is common but not certain that dc tests have a good immunity to ac noise.

6.5 Reactive component of impedance of a large grounding system

While small ground grids are principally resistive, large grids can be highly reactive, especially considering the real component of the impedance is commonly small compared to the reactive component (Harrison [B48]). Certain precautions are necessary when measuring the power frequency (usually either 50 Hz or 60 Hz) impedance of a large grounding system. For such measurements, the test devices are operated at a test frequency that is slightly above or below the power system frequency to obtain ac noise rejection during the test. A frequency sweep can be used to provide information to allow the results to be corrected to the appropriate power frequency and thereby be more accurate.

6.6 Coupling between test leads

Inductive coupling can occur between components of two or more ac circuits by means of the mutual inductance that associates the 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 test current flowing in the current lead (or other paths), is included in the measured voltage and needs to be assessed and possibly corrected. The 50 Hz or 60 Hz inductive coupling between two parallel test leads might be as high as 0.1 Ω /100 m (0.1 Ω /300 ft). As a result, the error can be appreciable because low ground impedance usually occurs in ground grids that cover large areas, and long test leads are typically required to reach remote earth. Thus, coupling between test leads can introduce large errors when a ground grid covering a large area has a relatively low impedance.

Conversely, a ground grid that covers a small area usually has a relatively high ground impedance, 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, and low-impedance grounds. As a rule of thumb, test lead coupling is usually negligible on measurements of grounds that are 10 Ω or greater, but it is almost always important on measurements of 1.0 Ω or less, and can be significant in the range between 1.0 Ω and 10 Ω .

Test lead coupling can be reduced by appropriately routing the potential and current test leads. When test lead coupling is anticipated, separating the leads or running the test leads in perpendicular directions may reduce test lead coupling.

6.7 Interference from conductive objects

Partially or completely buried conductive objects, such as fences, rails, and metallic pipelines, located in the vicinity of the soil, ground grid, or grounding system being tested, may have considerable influence on test results (Dawalibi and Mukhedkar [B33], Rudenberg [B84]). Soil potential contours are distorted, and voltage gradients are increased, when measured near conductive objects.

Whenever the presence of conductive objects is suspected in the area where measurements are to be performed, and the location of these objects is known, the influence of these objects on the measurement must be considered and recorded. Locate test probes as far as possible from buried structures (unless the intent of the test is to assess these structures). Where this is not possible, aligning the test probes in a direction perpendicular to the routing of these structures can assist in error determination and correction.

6.8 Other sources of error

Test equipment with different probe layout configurations and units of measure may require caution during testing and analysis. Practitioners should confirm that data points were taken with the same test method, probe

layout, reference points in space, and units of measure before comparing tests. For example, Wenner and Schlumberger methods have different penetration depth and spacing distances.

Different types of test equipment can cause issues with units of measure (e.g., $\Omega \cdot \text{m}$, $\Omega \cdot \text{cm}$, $\Omega \cdot \text{ft}$), and variations of units can be challenging for conversion. Some soil resistivity test instruments only provide resistance measurements; some provide only resistivity. Resistivity can have variations of meters and feet in distance between probes and $\Omega \cdot \text{m}$ values. Test instruments that report values in resistivity require the probe spacing to be input for each measurement or errors will result.

Other issues include the following:

- a) Individuals can make mistakes of inclusion or omission.
- b) Incorrectly configuring leads can give errors, but in some cases, they may not be noticed immediately. Care is recommended to conduct checks regularly including “sanity checking” measured results.
- c) Injected power should be considered as too little can lead to errors and too much may be hazardous.
- d) Battery-powered equipment with less than adequate working time can lead to adequate testing not being completed in the scheduled site time.
- e) Test instruments may require particular action (procedures). Manufacturer’s instructions should be read and understood prior to testing.

7. Electrical soil resistivity

7.1 Overview

Electrical soil resistivity (ρ) is an important component of many parameters used in assessing grounding system designs. Since soil resistivity may vary from under $1.0 \Omega \cdot \text{m}$ to $10^9 \Omega \cdot \text{m}$, the performance of grounding grids with such varying electrical parameters can be challenging to predict. The grounding specialist is tasked with balancing accurate geological soil interpretations using well-developed geotechnical methods, with electrical performance characteristics of grounding systems installed in varying soil conditions. Common soil electrical resistivity test methods for grounding purposes include the Wenner, Schlumberger, Palmer, and driven rod methods. The measured data is then used to develop electrical soil models for use in grounding grid design, safety performance assessment, and other power system analysis (e.g., line impedance calculations).

7.2 Electrical parameters affecting soil resistivity

7.2.1 Type of material

Soil often comprises a layered structure with topsoil over one or more layers of various types of materials. These materials rest on bedrock, also often stratified. [Figure 1](#) shows examples of resistivity (ρ) values for various geological materials. The extent in these ρ ranges and the difference seen for sandstone, for example, underline the need to measure soil resistivity local to the grounding system under consideration. [Figure 1](#) should not be used to estimate or assume a soil resistivity or soil model based purely on soil type or geological period. Field testing is required.

Earth resistivity ($\Omega \cdot m$)	Quaternary	Cretaceous Tertiary Quaternary	Carboniferous Triassic	Cambrian Ordovician Devonian	Precambrian; 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	Coarse sand and gravel in surface layers				
3000 - Very high					
10 000 - Extra high					

Figure 1—Geological periods and rock formation (Sunde [B89])

Topography can give clues about the water table depth and the consistency of the variation of resistivity values in soil. For example, groundwater, which may lower the resistivity, is likely to be absent or low in sandy soils and concentrated near rivers, lakes, or the sea. Resistivity could change with location and elevation in hilly terrain, while it may be more consistent in flat areas. Having some knowledge of the geology in the tested area may help corroborate changes in resistivity seen with depth. However, field testing is required.

7.2.2 Salt, moisture, and temperature

Earth resistivity varies not only with the type of soil but also with temperature, moisture, and mineral content. Figure 2 shows an example of curves for a particular soil sample (sandy loam) and compactness (Towne [B94]). They are a useful insight into dependency trends associated with the ionic conduction mechanism but cannot be used to accurately scale to other soils, or even the same soil sample with different compaction. The resistivity of the soil increases slowly with decreasing temperatures from 25 °C to 0 °C. Below 0 °C, the resistivity increases rapidly. This increase in resistivity may be used by grounding specialists to account for frozen soil, although the increase may be smaller in other types of soils. Water resistivity values range from less than 1 $\Omega \cdot m$ in the sea (Abedu [B1]) to over 5000 $\Omega \cdot m$ in some rainfall (Bellasi [B12]). Lower soil resistivities are often found near the ocean, in central prairies (due to soil mineralization), adjacent to agricultural lands (due to fertilizer), by roads (if winter salt has been applied), and in industrial areas (due to pollution). However, even with the above insight, visual inspection rarely yields dependable results. Field testing is required.

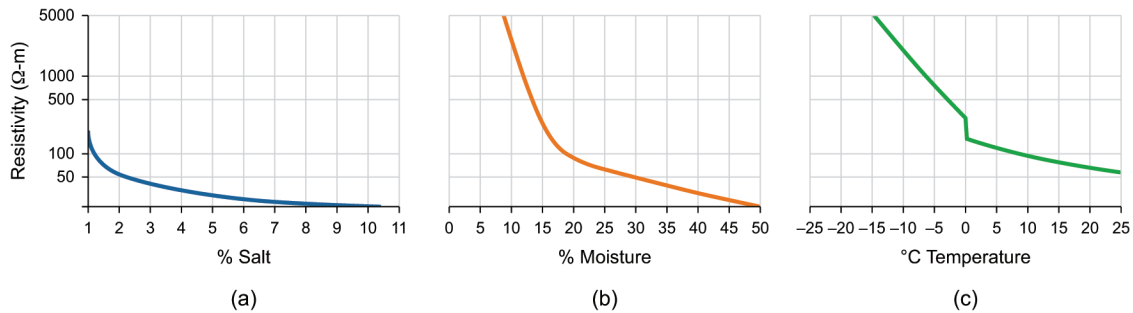


Figure 2—Example of effect of salt, moisture, and temperature on soil resistivity (sandy loam)

In some regions of the world, it is common for soil resistivity test reports to include information regarding the season and weather conditions, including the ambient temperature. However, soil temperature and water content at depths below 1 m (or to the frost depth if larger) remain fairly constant through the year in most cases. The resistance of larger ground grids, especially where deeper electrodes are installed, may depend on deeper soil resistivity values and may be less subject to seasonal changes. Tests conducted under wet conditions may result in values lower than those present during dry conditions, and this could be accounted for in the assessment and the design stages.

7.3 Methods of measuring soil resistivity

7.3.1 Introduction

Earth electrical resistivity can be measured in many ways and for many different purposes. Wenner, Schlumberger, and Palmer are examples of tests using four probes in a line (or traverse) with various spacings. Although these were originally developed for nongrounding applications, the power industry has been using them for grounding-related purposes for decades. For each of these test methods, a test current is injected between two probes and potential is measured between the remaining two probes. Test instruments commonly display the result as a measured resistance R and/or an apparent resistivity ρ_a . The typical unit of measure is ohm-meter. Large probe spacings provide apparent resistivity measurements more affected by soil at a large depth. The more important an accurate deeper soil resistivity is in the analysis or design of the grounding system (with respect to its compliance or performance), the larger the spacings are required to be in the testing traverse, or the deeper the test rod should be in the case of the driven rod method.

For all test methods, it is recommended that, as each test measurement is made (usually starting from the closest spacing), the apparent resistivity is calculated, and the results plotted. For each calculated resistivity measurement, the following questions could assist the test crew:

- Is this ρ or R value believable based on a sound understanding of the soil, geology, and geography?
- Is this ρ or R value believable in terms of the trend that is being plotted? Is there a reason to check the test setup or to remeasure this spacing?
- Is there a reason to take an extra reading between this one and the last to better understand an apparent change?
- Are the ρ or R readings indicating homogenous soil, are they indicating horizontal layers, or is there something else that needs to be understood or investigated further?
- Has the apparent resistivity flattened enough, over adequate distance, to be confident about the underlying resistivity?
- Should the traverse be extended to another reading at a greater spacing (or should the driven rod go deeper)?

Having run out of lead length or physical space in a particular location is not a good reason to finish testing at a site.

Consideration should also be given to taking reciprocal measurements at each spacing as a means of detecting error in the configuration or possibly a high ground resistance on one or more probes. See 7.4.5.

7.3.2 Wenner method

The Wenner method [B95] is the most common soil resistivity test. Four probes in line have equal spacing a (Figure 3). b is the probe burial depth. A traverse includes repeated measurements with spacing a typically increased over a range. An example of a Wenner array traverse is composed of multiple electrode spacings a , where a takes values of 0.5 m, 1 m, 2 m, 3 m, 5 m, 7 m, 10 m, 15 m, 20 m, 30 m, 50 m, 70 m, 100 m, 150 m, and 200 m. The close a spacings provide top layer soil resistivity information that is important when modeling touch and step voltages. The larger a spacings provide more information about the resistivity of deeper soil layers.

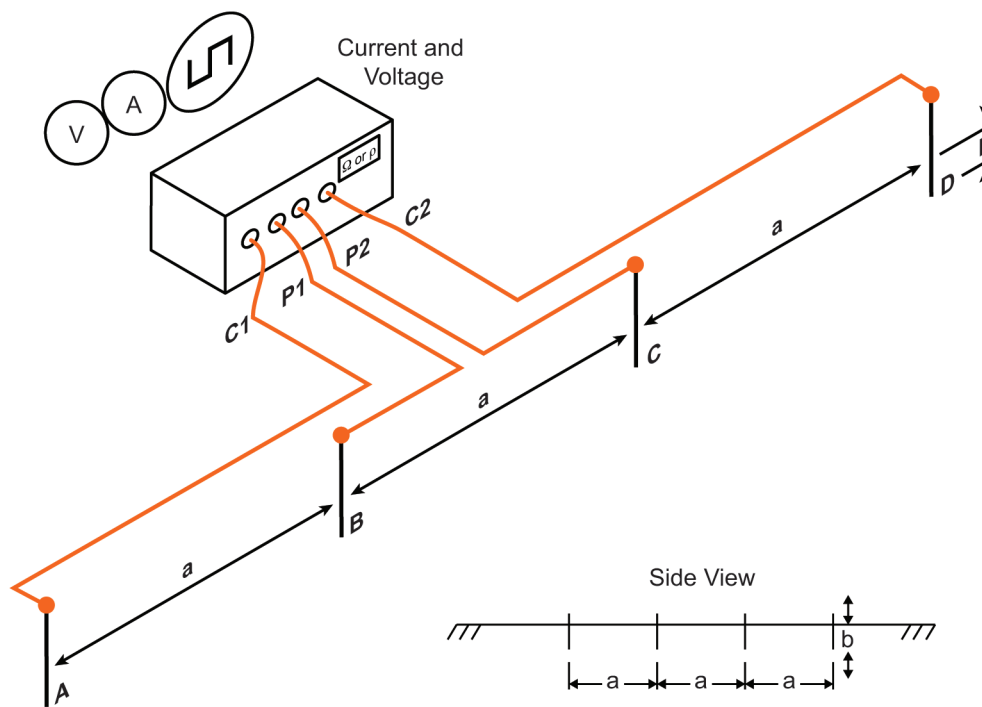


Figure 3—Wenner method

Completing a traverse using the Wenner method provides a series of numbers for apparent resistivity that should be plotted against the test spacing for each value. A trend line through the data points provides insight into the soil layering; information that is critical for ground grid assessment and design purposes.

Table 1 shows examples of two different Wenner traverses in two contrasting soil types (this example is from a simulation). The first traverse has a layer with 6.1 m thickness of $300 \Omega \cdot \text{m}$ soil above a deep layer of $100 \Omega \cdot \text{m}$ soil. The second traverse has a layer of 6.1 m thickness of $100 \Omega \cdot \text{m}$ soil above a deep layer of $300 \Omega \cdot \text{m}$ soil. Note that the measured apparent resistance decreases with increased probe spacing. This means that for large a spacings such as 200 m in $30 \Omega \cdot \text{m}$ uniform soil, the resistance is only 24 m Ω , which calls for an instrument with good resolution.

Table 1—Example of Wenner traverses' resistance and apparent resistivity

Probe spacing a (m)	$\rho_1 = 300, \rho_2 = 100, h = 6.1 \text{ m}$ (20 ft)		$\rho_1 = 100, \rho_2 = 300, h = 6.1 \text{ m}$ (20 ft)	
	R (Ω)	ρ_a ($\Omega \cdot \text{m}$)	R (Ω)	ρ_a ($\Omega \cdot \text{m}$)
1	47.7	300	15.9	100
2	23.6	297	8.06	101
5	8.45	266	3.62	114
10	3.05	192	2.38	149
20	0.986	124	1.62	204
50	0.326	103	0.841	264
100	0.160	101	0.457	287

In Table 1, three significant figures are not reflective of achievable accuracy in field measurement; however, they were used in these simulations to show the true smoothness of the curves. Real field data is typically more uneven and presents bumps in the curves.

The apparent soil resistivity ρ_a is computed with Equation (1).

$$\rho_a = 2\pi a R \quad (1)$$

where

- ρ_a is the apparent resistivity, in $\Omega \cdot \text{m}$
- a is the spacing between the probes, in m
- R is the apparent resistance measurement, in Ω

The apparent resistivity was included in Table 1 and plotted for the two soil types in Figure 4. At small and large probe spacings, ρ_a approaches the top and second layer resistivity, respectively.

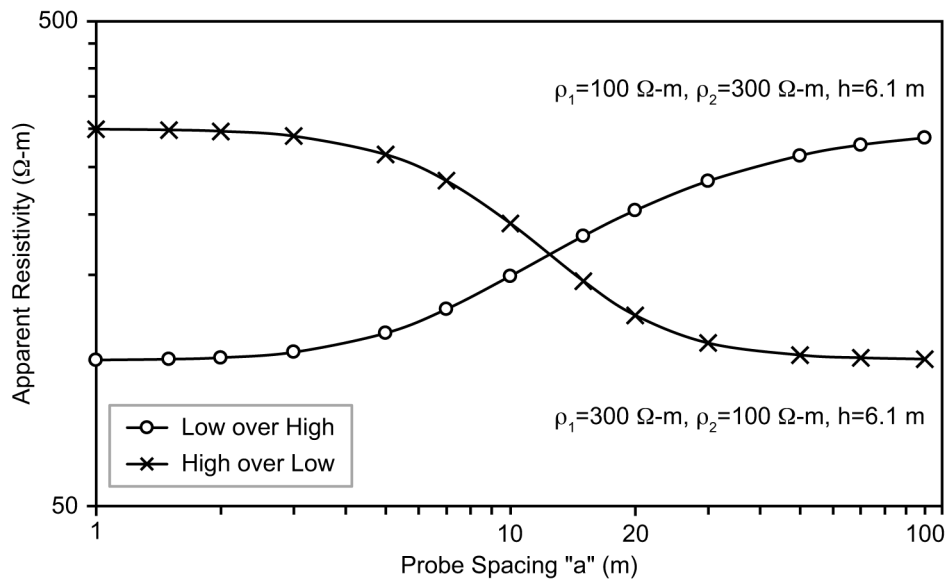


Figure 4—Wenner traverse apparent resistivity plotted from Table 1

For small probe spacings with probe depth b exceeding $0.1 \times a$, the apparent resistivity is better represented with Equation (2).

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

where

- ρ_a is the apparent resistivity, in $\Omega \cdot \text{m}$
- a is the spacing between the probes, in m
- R is the apparent resistance measurement, in Ω
- b is the depth of the probe, in m

Equation (2) accounts for the depth of the probes into the soil.

7.3.3 Schlumberger method

The Schlumberger method (Figure 5) has the voltage probes at a smaller distance d (compared to Wenner) while the current probes are moved outward by increasing distances c to investigate deeper soil structures. The Schlumberger method does provide much smaller resistance readings for large c spacings of the current probe, so a test instrument with higher test power and resolution may be needed. Distance d may need to be increased periodically so the ratio c/d remains less than 30 to maintain a reasonable meter resolution. Some interpretation software may require that the value $((2c + d)/d)$ remains larger than 5 (or the ratio of distances AB and MN is greater than 5).

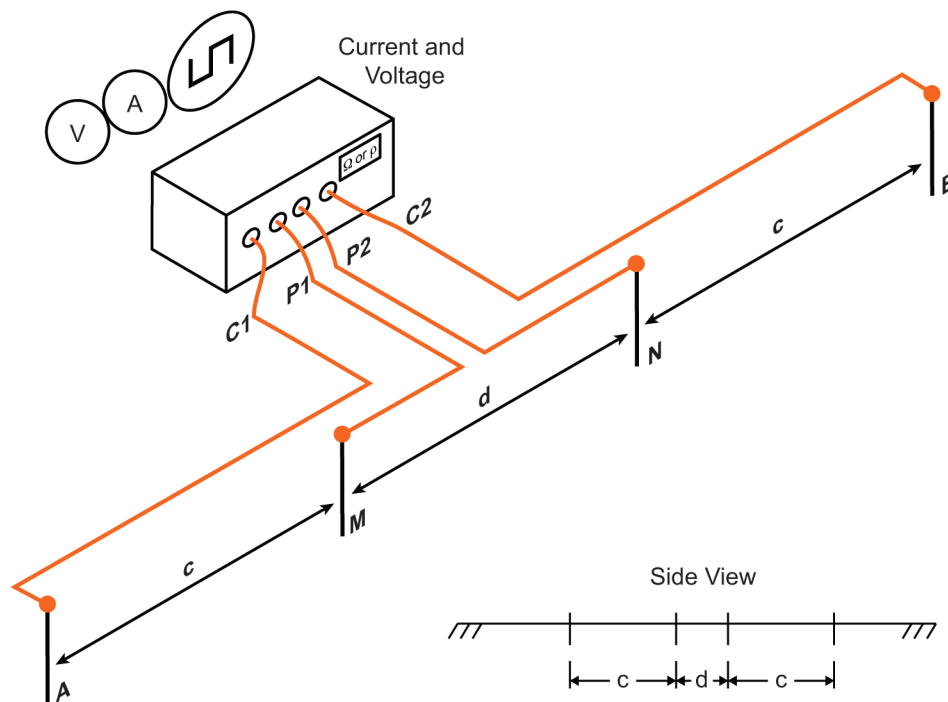


Figure 5—Schlumberger or Palmer method

The high upper layer resistivity of sandy areas (or when testing in frozen soil) can make it difficult to achieve a sufficiently low contact resistance for the current probes. The reciprocity theorem for linear networks allows current sources and voltmeters to be interchanged. Thus, this procedure may be used as a field check to detect possible errors. Resistance readings should remain unchanged with current applied to the inner probes and voltage sensed on the outer probes. This allows driving the fixed inner probes to a greater depth, adding nearby multiple probes, or applying salty water to reduce the probe contact resistance.

The apparent soil resistivity ρ_a is computed with Equation (3).

$$\rho_a = \pi c(c + d)R/d \quad (3)$$

where

- ρ_a is the apparent resistivity, in $\Omega \cdot \text{m}$
- c is the spacing between the current and potential probes, in m
- d is the spacing between potential probes, in m
- R is the apparent resistance measurement, in Ω

Table 2 shows simulated resistances that could be measured using two Schlumberger traverses for the two soil types considered for the Wenner array above (this simulation follows the same scenarios from Table 1). Apparent resistivity was included in Table 2 and has been plotted in Figure 6. At small and large c probe spacings, ρ approaches the top and second layer resistivity. Schlumberger apparent resistivities are usually plotted against half the distance of A to B ($(2c + d) / 2$). Thus, c in Table 2 includes fractional values. Slight discontinuities occur in Figure 6 when d changes, while the ratio $AB/2$ is maintained constant.

Table 2—Example of Schlumberger traverses' resistance and apparent resistivity

Probe spacing			$\rho_1 = 300, \rho_2 = 100, h = 6.1 \text{ m}$		$\rho_1 = 100, \rho_2 = 300, h = 6.1 \text{ m}$	
c (m)	d (m)	$AB/2$ (m)	R (Ω)	ρ_a ($\Omega \cdot \text{m}$)	R (Ω)	ρ_a ($\Omega \cdot \text{m}$)
0.75	0.5	1	50.9	300	17.0	100
1.25	0.5	1.5	21.8	300	7.29	100
1.75	0.5	2	12.1	299	4.06	100
2.25	0.5	2.5	7.66	298	2.59	101
2.75	0.5	3	5.27	296	1.81	102
2	2	3	23.6	297	8.06	101
4	2	5	7.57	285	2.80	106
6	2	7	3.54	267	1.50	113
9	2	10	1.49	232	0.826	129
7.5	5	10	4.00	236	2.15	127
12.5	5	15	1.32	181	1.12	154
17.5	5	20	0.592	147	0.718	178
27.5	5	30	0.208	117	0.376	211
37.5	5	40	0.108	108	0.233	233
30	20	40	0.466	109	0.973	229
40	20	50	0.279	105	0.652	246
60	20	70	0.136	102	0.352	265
90	20	100	0.065	101	0.180	280

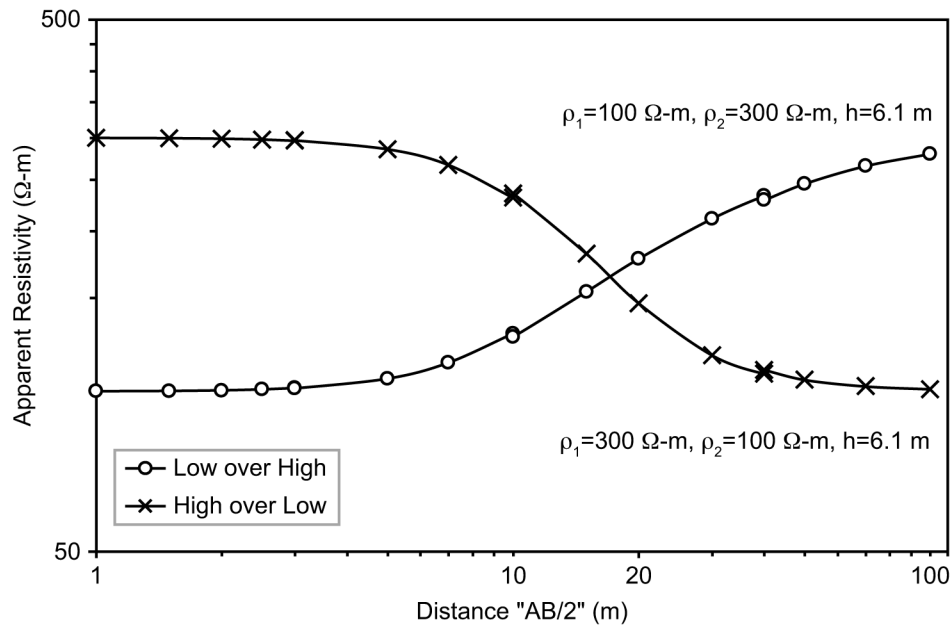


Figure 6—Schlumberger traverse apparent resistivity plotted from Table 2

7.3.4 Palmer method

The array of the Palmer test method [B77] is like the Schlumberger array (Figure 5), except that distance c is made smaller than distance d . This increases the measured resistances substantially (even higher than for Wenner) but places a focus on near surface soil in the area between the A and B probes. This makes deep soil structures more difficult to resolve due to mathematical model constraints.

7.3.5 Driven rod method

The driven rod method measures soil resistivity from the resistance of a test rod of radius r driven to increasing depth l (Figure 5). An alternative approach is to install a conductor into an existing unlined borehole, stopping at a various depth to take measurements. The borehole is commonly backfilled using a low-resistivity wet bentonite gypsum mixture (or similar), to allow the conductor to both make good electrical contact and ease of installation. The boreholes may already be available due to geotechnical soil sampling.

In Figure 5, terminals C1 and P1 of the test instrument connect to the driven rod while terminals C2 and P2 run to remote probes using methods outlined in Clause 8. The driven rod method may be well suited to congested areas where it is difficult to apply large Wenner spacings to assess the resistivity of underlying layers.

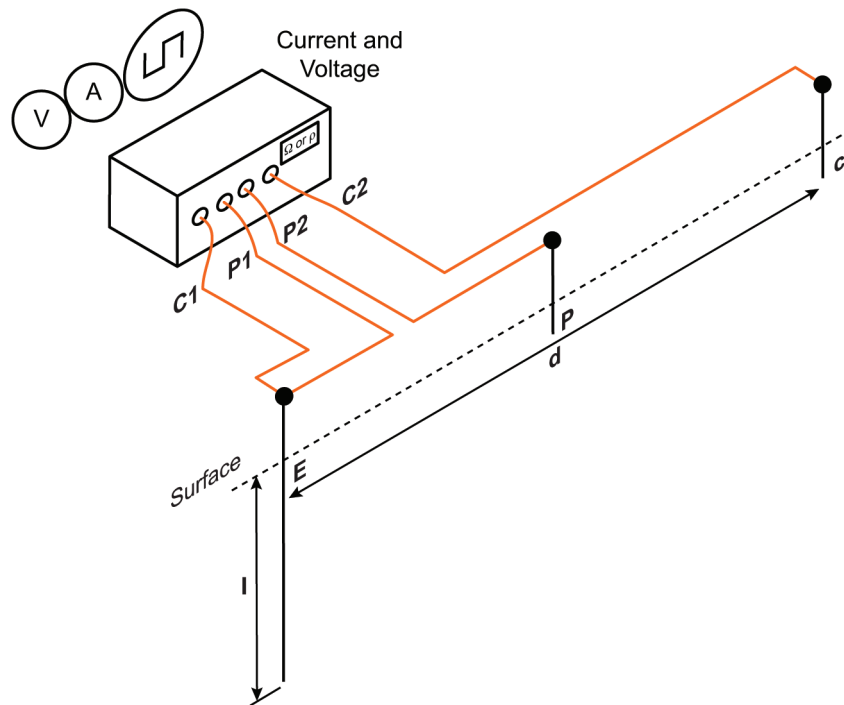


Figure 7—Driven rod method

Remote current probe C is commonly located 10 times the maximum rod depth.

Table 3 shows the resistances that were calculated to simulate measurements taken using two driven rod traverses for the two soil types considered above for the Wenner and Schlumberger examples. The apparent soil resistivity ρ_a is computed with Equation (4).

$$\rho_a = \frac{2\pi R l}{\ln(4l/r) - 1} \quad (4)$$

where

- ρ_a is the apparent resistivity, in $\Omega \cdot \text{m}$
- R is the resistance measurement, in Ω
- l is the depth of the driven rod, in m
- r is the radius of the rod, in m

Apparent resistivity was included in Table 3 and has been plotted for the two-layer soil in Figure 8.

At shallow and large rod depths, ρ values approach the top and second layer resistivity. The resistivity experiences an inflection point when the rod penetrates the second layer.

Table 3—Example of driven rod traverses' resistance and apparent resistivity

Depth l m (ft)	$\rho_1 = 300, \rho_2 = 100, h = 6.1 \text{ m}$		$\rho_1 = 100, \rho_2 = 300, h = 6.1 \text{ m}$	
	R (Ω)	ρ_a ($\Omega \cdot \text{m}$)	R (Ω)	ρ_a ($\Omega \cdot \text{m}$)
0.3 (1)	648	299	218	101
0.9 (3)	271	297	92.7	101
1.5 (5)	177	295	61.5	102
3.0 (10)	97.6	290	35.1	104
4.5 (15)	67.9	285	25.4	107
6.1 (20)	50.8	273	20.6	111
9.1 (30)	21.8	166	18.2	139
15.2 (50)	10.9	130	14.6	173
21.3 (70)	7.41	118	12.2	194
27.4 (90)	5.64	113	10.4	208
33.5 (110)	4.57	109	9.13	218
39.6 (130)	3.84	106	8.12	224
45.7 (150)	3.32	104	7.31	229

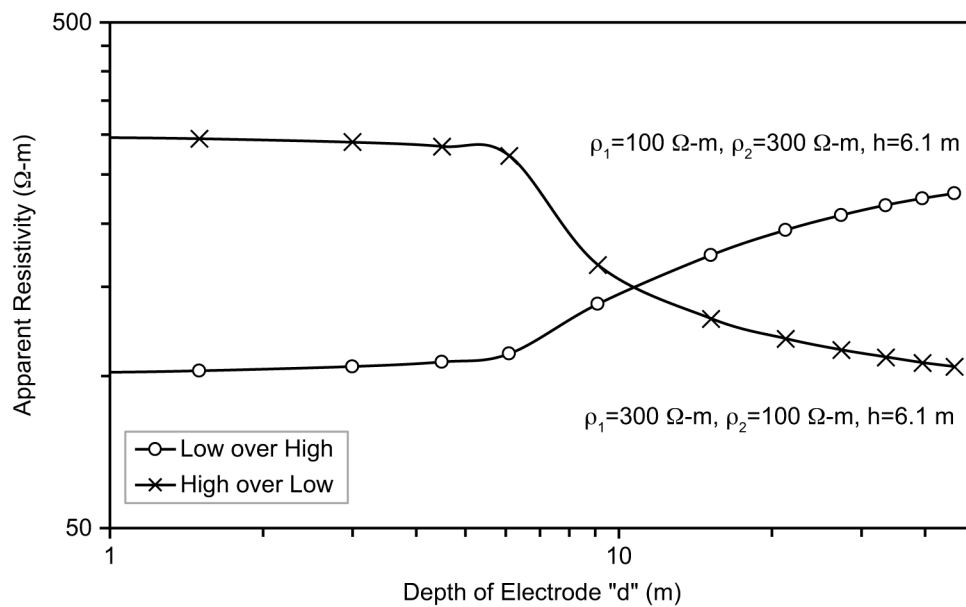


Figure 8—Driven rod traverses apparent resistivity plotted from Table 4

7.3.6 Geological information and soil samples

Extensive geotechnical soil boring may be performed at sites before construction, providing soil samples along with information on the following:

- Type of soil in each layer
- Moisture content
- Depth of water table
- Soil core resistivity values

A novel approach is to use soil or rock samples obtained from bore holes to directly measure the sample resistivity; however, these should not be used in isolation from other soil information. This method has challenges in maintaining the in situ soil density and moisture content and should be used with significant caution. It is useful to obtain resistivity data from multiple test samples, noting the depths of the test samples and included tolerances on the measured resistivities. Shallow bore samples, changes in water content, and uncertain compaction of soil in the test cell can cause errors that should be considered in the analysis.

Note that often laboratory testing is performed with samples fully saturated for the purposes of determining minimum resistivity; these values should not be used for grounding analysis.

7.3.7 Other geological methods

There are other methods within the field of geophysics that may prove valuable in grounding measurement, assessment, and design. These methods include electromagnetic induction borehole probes, direct push (DP), and other electromagnetic sounding methods. Currently, these methods are not in use for grounding-related purposes, including design.

7.3.8 Comparison of resistivity test methods

Table 4 provides a comparison of advantages and disadvantages of soil resistivity test methods. The appropriate Clauses should be reviewed as needed for more information on each method.

Table 4—Comparison of soil resistivity test methods

Method	Pros	Cons
Wenner	Larger voltage across inner probes requires lesser meter resolution Less affected by central soil resistivity anomalies	Time consuming; four probes are moved at each measurement Lead mutual inductive coupling may produce error with some instruments
Schlumberger	Less time consuming; mostly, only two probes are moved for most test points Fixed current probes can be moved when contact resistance is very high	Smaller voltage across inner probes requires better meter resolution Sensitive to soil resistivity anomalies between center probes Lead mutual inductive coupling may produce error with some instruments
Palmer	Allows for highest soil resistance readings	Less accuracy when interpreting deep soil layers
Driven rod	Has more flexibility for lead deployment than for other traverses; works at sites with high congestion and/or little testing space	Requires boring if it is not possible to drive rods Interpretation software not common in industry
Geological information and soil sampling	May support soil resistivity values of other methods shown above Resistivity may be supported by other physical properties of soil	Soil compaction and water content likely to vary resistivity values when tested at different times Resistivity may be limited to shallow depths

7.4 Test planning

7.4.1 Instrumentation, test leads and probes

If testers are battery powered, the capacity should allow for taking multiple readings over a test day without needing to recharge or replace batteries. Some meters may give erroneous results when used under high humidity or winter conditions. Damaged insulation on test leads may affect the accuracy of measurements as test current may leak into the soil along the test lead length (e.g., the jacket is punctured).

The test current is usually a square wave, often with polarity reversal, commonly in the frequency range of 70 Hz to 150 Hz, or below 10 Hz. Inductive coupling between test leads can cause errors with some instruments, especially if the test leads are not fully unreeled. Even without coupling, coiled test leads can cause errors with some instruments simply due to the inductance. Repeating measurements at a different signal frequency can demonstrate that inductance and coupling errors are minimal.

Testing soil resistivity near power lines can add significant 50 Hz to 60 Hz interference to the measured potentials on long traverses, which may cause error. Reviewing manufacturers' specifications and/or bench testing (with a noise source) can determine an instrument's susceptibility to this error.

If the test instrument has a high-output voltage capability (commonly 200 V dc to 400 V dc), they are expected to better perform in very high resistivity soils. Some meters provide a warning to the operator when the contact resistances of current probes and/or potential probes are too high; however, other testers may have an increase in reading errors.

Lightweight test leads (e.g., 0.8 mm² or No. 18 AWG) may be easier to handle and large enough for the test current from most meters. However, care should be taken as mechanical forces may cause damage during deployment and recovery. Best practice is choosing test leads and connectors with good mechanical withstand to suit methods and environment.

Short metallic probes can be placed quickly during the tests. Cathodic potentials due to different metals are not an issue when using purpose-built meters. Standing dc voltages, including galvanic potentials, are usually averaged out by the polarity reversing dc method.

When testing in high-resistivity soil, the electrode contact resistance can be reduced, and thereby the test current can be increased, by applying water. Salt added to the water may also be of benefit (it lowers probe contact resistance). Alternatively, driving the probes deeper into the ground, or adding multiple probes at current locations, can lower resistance and increase the magnitude of the current signal. However, this practice increases the probe size and apparent depth, and compensation of measurements may be required.

7.4.2 Effect of seasons and weather

Shallow soil resistivity is more likely to be affected by seasonal changes or changes in weather. For soil near the surface, dry, rainy, and cold weather can make testing difficult (e.g., installing the test probes into the soil). Frozen soils reduce ionization of the electrolyte in the soil and increase test probe contact resistance. Areas with significant seasonal or water table variations can affect readings depending on what time of the year the test is conducted. All these cases should be identified and assessed with consideration.

7.4.3 Number of traverses

A minimum of two traverses running in different directions are recommended given that the soil may contain horizontal and vertical variation in resistivity. Several shorter and longer traverses can capture differences in resistivity. Proximity to metallic fences, transmission lines, distribution lines, and buried metallic bodies can lead to errors.

The larger traverses can capture deeper soil resistivity data that resembles the one at the site, even when the tests are performed distance away from the grounding system. In locations where long traverses are not possible, short traverses at or near the proposed site may provide useful shallow resistivity data, and these may be supplemented by additional long traverses taken further away, but in soil expected to be similar based on material, geographical and geological assessment.

7.4.4 Site selection

It is important to carefully select the location of traverses to obtain resistivity values that are representative of the site. Figure 9 shows an example of a proposed rectangular substation on the left, not yet built (greenfield site). Plans call for two traverses running in different directions, with a total span ($3a$ for Wenner or $2c$ for Schlumberger) extending to three times the diagonal dimension of the station. Traverses $1a$ and $1b$ provide the most localized information as they are conducted right on top of the future ground grid.

However, if Figure 9 represents a situation with an existing substation (brownfield site) located on the left side, the traverses $1a$ and $1b$ do not apply. Traverses need to be located some distance away from the existing ground grid, at locations $2a$ and $2b$. This solution avoids interference from buried conductors. Alternatively, in an existing site with limited space to test, traverses $3a$ and $3b$ may be placed closer to the existing substation, but may cause some error due to coupling to the substation ground grid, especially for larger spacings.

Caution should be used when selecting areas that will undergo earthwork, such as roads and stations. If the resistivity tests are performed prior to the earthwork, the results of the shorter probe spacing measurements may no longer be representative, and postgrading soil resistivity testing may be recommended. The site grading plan can provide information on impact on soil resistivity. The use of satellite imagery tools to pre-assess and develop proposed traverse layouts is beneficial.

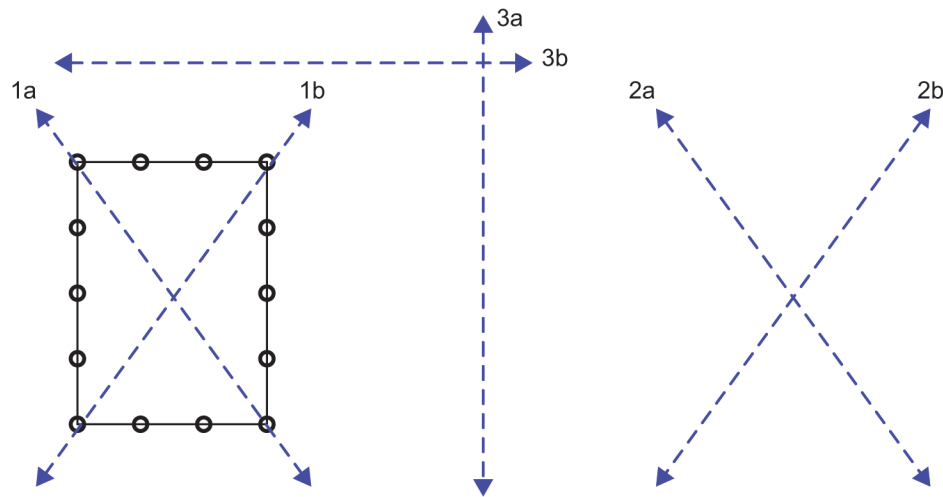


Figure 9—Examples of location of traverses at a greenfield/brownfield substation site

7.4.5 Size of traverses

To be able to produce a reliable electrical model of the soil, test traverses should include increased spacing until the measured apparent resistivity values present a stabilized value over a significant increase in spacing. This is usually identified when plotting apparent resistivity ρ_a versus probe spacing curve (on a log-log scale) after each measurement. For some purposes, a precise electrical model may not be required, and it is reasonable to tailor the number of traverses and traverse spacing to the required accuracy of the earth resistivity model.

Plotting the test results as the test crew increases the spacing can often identify soil measurements flattening to a consistent apparent resistivity. Ideally test spacing will be increased until this flattening occurs. In some cases, for example with a low resistivity over very high resistivity, it may not be possible or practical to continue spacings to the point of flattening plots. These limitations can be available space or test instrument limitations.

The length of a testing traverse affects the depth at which the apparent soil resistivity is being recorded. Tests often start with a small probe spacing such as 0.3 m to 1.0 m (1 ft to 3 ft), giving information about soil resistivity near the surface. In contrast, the modeling of electrode resistances requires traverses to include relatively large probe spacing. This is particularly true where a high-resistivity layer lies “hidden” under a relatively thick conductive top layer. Studies show that Wenner a probe spacing should reach the distances shown in Table 5 to avoid amplifying errors in resistivity data when calculating electrode resistance.

Table 5 is an example and cannot be used to choose a final traverse spacing based purely on grid size.

Table 5—Example probe spacing sensitivity

Electrode diagonal (Grid) (m)	Resistivity ratio (ρ_2/ρ_1)	Top layer h (m)	Final probe spacing a (m)
30	3	10	30
30	3	20	50
30	10	10	70
30	10	20	100
100	3	10	50
100	3	20	70
100	10	10	100
100	10	20	150
300	3	10	100
300	3	20	150
300	10	10	200
300	10	20	250

In Table 5, ρ_2 is the estimated bottom layer resistivity based on previous tests in the area. ρ_1 is the top layer resistivity, and h is the top layer thickness. For example, a 300 m (984 ft) diagonal grid placed on 20 m (66 ft) of $100 \Omega \cdot \text{m}$ soil located over $1000 \Omega \cdot \text{m}$ basement rock should have a probe spacing reaching 250 m (820 ft). This is considerably farther than usually done and may prove difficult to implement in congested areas. When probe spacings are limited to smaller values for practical reasons, the possibility of high-resistivity soil at depth should be considered when interpreting the results.

7.4.6 Density of probe spacings

The main goal of soil resistivity testing is to measure a profile of the variation of resistivity with soil depth. Increasing the probe spacing geometrically, for example, following 1 m, 2 m, 4 m, 8 m (or 5 ft, 10 ft, 20 ft, 40 ft) provides a uniform density of test points when the apparent resistivity is plotted on a log–log graph. Shallow soil layers need closely spaced probes. Changing to a uniform spacing for the last two or three probe locations provides redundancy in data for the deepest soil layer that can be difficult to resolve accurately.

Choosing round numbers for the spacings helps simplify placing the probes and facilitate communication among testing personnel. An example of spacings is 0.5 m, 1 m, 2 m, 5 m, 10 m, 20 m, 50 m, 100 m, 150 m, and 200 m (or 5 ft, 10 ft, 20 ft, 50 ft, 100 ft, 200 ft, 400 ft, 500 ft, and 600 ft). A higher density of probe spacings and a larger traverse such as 0.5 m, 1 m, 2 m, 3 m, 5 m, 7 m, 10 m, 15 m, 20 m, 30 m, 50 m, 75 m, 100 m, 150 m, and

200 m (or 3 ft, 6 ft, 10 ft, 15 ft, 20 ft, 30 ft, 50 ft, 70 ft, 100 ft, 150 ft, 200 ft, 300 ft, 450 ft, and 600 ft) may help to improve the interpreted model accuracy due to the additional data and deeper layers.

7.4.7 Proximity to other conductors

As traverses increase in their spacing, other conductors in the area can interfere with readings. For example, a test parallel to a conductive fence 15 m (50 ft) away may have no substantial error when the traverse spacing is less than 5 m (16 ft). However, as the traverse continues, the fence will act in part as a “shortcut” to the test current and make the underlying soil resistivity value be lower than the real value. The same traverse not parallel (but still in electrical proximity) to the fence will also lead to error, especially for the determination of underlying layer resistivity. Other examples of conductive interference include buried or aboveground pipelines, railway lines, buried cables with sheaths that leak current (ineffective insulated sheaths such as steel wire armored cables with jute serving), and steel reinforced concrete.

Best practice is to investigate potential buried conductors on site (e.g., a services search). Reviewing aerial or site photographs prior to testing may also be of value. Visual inspection once at site is also highly recommended. Signs of possible hidden items of concern can include easement pillars, and building or demolition works. Additionally, plotting test results as the crew carry on the tests can identify possible interference (e.g., a linear decline in apparent resistivity can often indicate conductive interference). Ideally, traverses should be routed in areas not containing or adjacent to buried conductors. Reciprocal measurements (reversing current and voltage leads) as described in (7.4.5) can identify conductive interference as a significant difference in the measured resistance values.

One study determined that errors in measured Wenner apparent resistivity values remain under 10% if the offset distance from a station ground grid is comparable to the maximum a probe spacing used in a survey (Blattner [B16]). However, the offset distance does not need to be larger than the size of the station.

7.5 Performing field measurements of soil resistivity

7.5.1 Safety considerations

A written job safety analysis with briefing should be conducted prior to testing. All team members should understand the testing process, be aware of potential safety hazards, and have the authority to stop the testing to resolve issues as they arise. Test personnel should maintain clearance from the test probes when energized by test sets injecting more than 50 V.

Test personnel must maintain communication to stay properly coordinated. Since probes are typically installed in the soil with hammers, Personal Protective Equipment may include eye protection and work gloves in addition to any site-specific requirements, such as high-visibility apparel. Measurement tapes should be nonmetallic (nonconductive). Permission to test should be obtained prior to measuring on private and public property. Utility locates should be requested. Avoiding damage to property (e.g., crops, vegetation, roadways) should be considered when testing.

7.5.2 Fixed or moving traverse center

The historic (and most common) approach is to conduct soil traverses around a fixed center when the spacing is increasing between measurements. However, some practitioners move the traverse center while increasing probe spacing (e.g., fixed end point method), which some consider a faster technique that requires only three long test leads and one short test lead. The fixed center is the most commonly used approach.

For soil that is homogeneous, or horizontally layered, over a large area, the errors will be small. For soil that has resistivity variations that are nonhorizontal layering, the errors can be significant, and the fixed center technique is recommended. In the field, it is often not clear what the soil structure is, and therefore, traverses with a moving center should be used with caution.

7.5.3 Recording test data

Best practice is for test personnel to plot apparent resistivity versus probe spacing on a log–log graph during the test in the field. Anomalies inconsistent with a smooth curve should indicate to the test crew that a check is needed of the instrumentation, the lead connections, and probe installation.

7.5.4 Sources of test error

Possible sources of test error include the following:

- a) Meter measures 50 Hz to 60 Hz interference
- b) Test probes with very large contact resistance
- c) Meter has insufficient resolution
- d) Meter has low-output voltage/power
- e) Meter is out of calibration
- f) Meter or test lead insulation are affected by rain
- g) Meter has low battery
- h) Test lead connections are incorrect
- i) Test lead conductor is broken inside the insulation jacket and not visible
- j) Test lead insulation is worn leading to alternative paths of current
- k) Mutual coupling is present between current and potential test lead reels
- l) Test leads are coiled providing sufficient inductance to cause instrument error
- m) Probes are not correctly located
- n) Probes are not placed in a straight line
- o) Capacitive, inductive, and conductive coupling is present due to proximity to stations, transmission or distribution lines, fences, or other buried conductive objects
- p) Soil structure is not homogeneous or horizontally layered
- q) Ambient temperature is above or below the accepted operating range of the test equipment

7.5.5 Error detection methods

Some errors in measurements can be detected by modifying the testing configuration in one of the following methods:

- a) The individual probe resistances may be approximately measured by connecting the probe to be measured to both the *P* (potential) and *C* (current) terminals of that side of the traverse and disconnecting the otherwise connected probe. Making this measurement for all four probes may identify high-test probe resistances that can significantly contribute to error. Some instruments conduct test probe resistance measurement automatically or manually.
- b) Conduct a reciprocity test that consists of in swapping the *C* and *P* test probes (both sides, that is, swap *C*1 and *P*1 and swap *C*2 and *P*2) at the meter and retake the measurement. The measured resistance should be the same value or very similar to the measurement before swapping probes due to reciprocity.

7.6 Interpreting soil resistivity models

7.6.1 Choosing the number of layers to interpret

A two-layer resistivity model can provide adequate accuracy when the underlying soil contains a single interface, such as a uniform upper soil layer over a single type of rock or permeable soil above and below the water table.

Three-layer models may be needed when either the soil or the rock have greater complexity, or when frozen soil near the surface is considered. Three-layer models are especially necessary when the apparent resistivity plot shows a “sandwich” layer structure, with the middle layer either higher or lower in resistivity than the outer two layers. This is because when a soil layer resistivity changes from a low magnitude to a high magnitude (relative to each other), current tends to stay within the low-resistivity soil. This tends to cause voltage gradients to extend further from an installed ground grid rather than if the soil was uniform with a low-resistivity value. If subsequent deeper layers in the soil are of a lower resistivity, measurements of the magnitude of the bottom layers can be difficult to assess since the high-resistivity layer will significantly affect the measurements at larger spacings. However, the goal of characterizing the effective electrical performance of the soil is important. Assessing a representative number of layers depends on other factors such as the following:

- a) The size of the ground grid to be installed (or is already installed) (e.g., large substation, small distribution pad, small pipeline appurtenance, wind turbine footing),
- b) The type of effects to be studied (e.g., grounding safety, electromagnetic ac interference studies, transmission line shielding performance)

Assessing the number of layers to interpret depends on the magnitude of resistivity from one layer to the next and can have a significant effect on a grounding grid design. In many cases, the use of one or more simplified models can be effective and efficient.

Increasing the number of soil layers in the model can help reduce the calculated rms error. This may, however, be a misunderstanding since a model with sufficient degrees of freedom may fit any number of data points. Improving the curve fit by adding additional soil layers may decrease the accuracy of the calculated grounding results when there are errors in the soil resistivity data set. It will not improve the accuracy of the calculated electrode resistance or the touch and step voltages if the apparent resistivity data has error due to the sources mentioned in 7.4.4.

7.6.2 Consolidating multiple traverse data sets

When multiple traverses show significant variation in resistance or resistivity values, they should be individually interpreted. The final model could be based on a combination of the results. However, differences may arise due to proximity to conductive objects; the need to test in less congested areas some distance away; localized anomalies in the soil; large probe contact resistance; interference from power lines; or due to limited resolution in the testing meter on long spacing surveys.

When multiple traverses have data points that are similar in value, the user may choose to combine the results before interpretation to reduce the effect of soil anomalies, interferences, or instrument noise. Caution is required.

Where testing areas local to the grid are congested and only allow short surveys (to avoid interference), longer traverses may not be possible. It is recommended to test in a more open area near the site (judged to have similar soil resistivity). Geological investigation and review of results from previous resistivity testing or borehole data in both locations may help demonstrate that deep strata are similar and may have comparable soil resistivity values.

If practical, differences in terrain elevation should be avoided since deep strata points may or may not remain at a constant elevation. Longer traverses must be interpreted individually, with the upper layer resistivity values discarded if they represent soil that is different from the site of interest. [Annex G](#) provides an example of this process.

7.6.3 Interpretation methods

Commercial grounding software can provide a way to interpret apparent resistivity test data into a multilayer soil model. When this option is not available, a two-layer model can be obtained using a graphical method described in [Annex H](#). A method that takes advantage of the optimization function typically available in spreadsheets is described in [Annex I](#).

8. Ground resistance testing

8.1 General

The methods used to measure ground grid resistance presented in this clause have been used since the 1930s. For many electrical grounding systems, the grid resistance (R_g) provides key information in assessing the GPR. The most common methods for measuring grid resistance covered in this part of the guide are the two-point, fall-of-potential, and slope methods. The methods are a combination of data acquisition and interpretation of the test results.

The measurement methods are principally concerned with accurately measuring the ground grid resistance of a stand-alone ground grid where no other electrical grounding interconnections are present.

Instruments using induction coils (commonly in the form of a clamp-on ammeter) are also discussed as a method for resistance measurement. These instruments can be used for measuring a loop resistance in a similar way to the two-point method. They provide useful results for resistance dominated loops.

8.2 Background

8.2.1 Historical development of test methods

The need for measuring the resistance of buried grounding grids was developed shortly after the widespread implementation of a grounded three-wire and four-wire system. Protective relays of equipment protection systems require a low enough ground grid resistance to detect ground faults. Thus, the requirement of certain minimum ground grid resistance values was implemented depending on the asset. Over time, the design practice of using target grid resistance values was expanded to most electrical installations. This practice affected system performance across power generation, transmission electrical substations, transmission lines, and distribution substations down to distribution loads.

8.2.2 Design resistance values across asset types

The following list includes different types of assets where design resistance values may be used:

- a) **Electrical substation ground grids:** Measuring R_g can be used for the assessment of design grid resistance targets for ground grids without any electrical interconnections or for ground grids prior to interconnection.
- b) **Power generation ground grids:** The ground grid resistance is often used in the assessment of GPR for smaller power generation ground grids not connected to large electrical substations, penstocks, wind farms, solar farms, or other networks.

- c) **Transmission line lightning performance:** The design of high-voltage and medium-voltage transmission lines often require target tower footing resistance values specifically for lightning performance.
- d) **Transmission power cable performance:** High-voltage power cable splices and sheath voltage limiters often require target ground grid resistance values for dissipation of transient and power ground faults.
- e) **Distribution and multigrounded neutral network performance:** The performance of three-wire grounded systems require target resistance values at the meters and customer loads to allow for protection systems to operate correctly. Multigrounded neutral (MGN) network ground points require minimum pole resistance values required to meet safety and performance requirements of the system.
- f) **Communication and cellular telephone towers:** Targeted resistances to limit GPR and voltage differences are common and technology dependent.

8.2.3 Common sources of error and instrumentation considerations

Common sources of error introduced by the grid resistance measurement methods include the following:

- a) **Mutual earth resistance (MER):** In circumstances where the remote current electrode is not installed beyond the influence of the ground grid under test, MER will occur between the two grids. This error is nonconservative and not commonly detected. Analysis techniques can be used to detect and correct these errors in most circumstances.
- b) **Inductive and conductive interference:** Between the test circuit and a buried or aboveground metallic infrastructure, this interference can cause error. Buried pipelines and metallic fences can cause some of the test current to divert and flow along the pipe and fence rather than through the soil. The result is typically the lowering of the apparent resistance compared to the case when metallic infrastructure is not proximate or does not provide the same “shortcut” in a real scenario. Transmission line shield wires or distribution MGN can interfere in a similar way and will typically reduce the apparent resistance. Other infrastructure, such as large steel-reinforced concrete structures (e.g., bridges, foundations, dams), can also significantly influence the measurement. Inductive interference is usually not a source of error when using a dc test signal.
- c) **Test lead inductive interference:** Between test leads, this interference can affect the measurements. When the voltage test leads are run parallel to current test leads, the EMF induced on the voltage measurement circuit can be a significant source of error with ac and switched dc measurements for some instruments.
- d) **Loop inductance:** Test lead or other circuit inductance can lead to errors in switched dc measurements for some instruments and/or some configurations. This error relates to loop inductance large enough to cause the transient at dc polarity reversal to extend inside the measurement window. The errors are nonconservative. To help reduce the risk of this error, test leads should be fully unreeled during measurements.

A discussion of instrument development for measuring grid resistance in the power industry is provided in [Annex D](#).

Ground resistance meters can be two-terminal or four-terminal measurements, as follows:

- **Two-terminal resistance instruments** combine the test signal and measurement signals. This method has some advantages and drawbacks as outlined in the following subclauses. However, the voltage drop along the test leads can be a significant source of error.
- **Four-terminal resistance instruments** separate the measurement circuit from the injection circuit. Most implementations of four-terminal ground testers use a switched dc signal to offset small standing