CONNECT AND PROTECT

Ground Electrode Design Principles and Testing

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TABLE OF CONTENTS

Ground Electrode Design Principles and Testing

ABSTRACT

This paper captures the fundamental principles of ground electrode design, ground resistance and soil resistivity measurements and computations. It will form a basis for understanding the reasoning behind incumbent grounding practices and will act as a guideline to an engineer trying to grasp the essence of ground electrode design.

1. Explanation of ground sheath theory.
2. Explanation of what soil resistivity and ground resistance is.
3. Effect of soil resistivity and electrode dimension on the ground resistance.
4. Calculation of ground resistance from known dimensions and soil resistivity measurements.
5. Discussion on parallel ground electrodes and calculation of resistance for parallel ground rods.
6. Methods of testing soil resistivity and ground resistance.

DISTRIBUTION OF VOLTAGE IN GROUND – SHEATH THEORY

To understand grounding principles, the first thing that we will consider, is how the voltage is distributed in the Earth when a current is injected into a vertical ground rod. The intuitive understanding of this will enable us to better appreciate why electrode designs are done a certain way. For example, this will help us to understand why we use deeper ground electrodes or radial electrodes.

The soil is non-uniform in its conductivity and this factor will need to be accounted for in the design of the ground electrode system. However to develop an understanding of the principles of the current flow and the voltage distribution in the ground, we will look a graphical model, which assumes uniform soil. This is called the sheath theory of expanding soil conductivity. In Figure 1, the hemispherical sheaths depict imaginary equipotential lines, which form in the ground when a current is injected into a vertical ground rod.

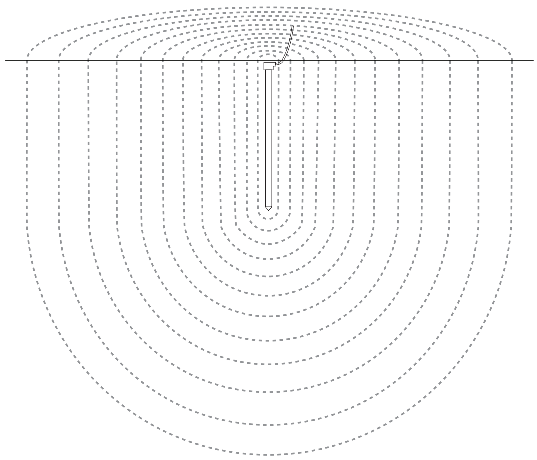


Figure 1: Equipotential lines caused in ground when a current is injected in a vertical ground rod. (Sheath Theory)

THE ELECTRODE RESISTANCE

The electrode resistance is that resistance offered to the flow of current into the ground down to the expanse where the resistance of the ground becomes so low that it becomes negligible.

Consider the cut away section of the sheaths surrounding the ground electrode in Figure 1. In simple terms this resistance can be explained by the following relationship.

$$R \propto 1/A$$

where R is the resistance and A the area of each of the sheaths.

As the distance from the ground rod increases, the surface area of the sheaths, get larger. This means that at some distance, the additional soil area has negligible effect on the ground resistance.

It is for this reason, when measuring ground resistance to a remote earth, the test only needs to be confined to few tens, perhaps a few hundred of meters. For example, when testing a single 2-meter electrode, the test is only referenced to remote earth at distance of about 60-100 meters. Any greater reference distance than this would add insignificantly to the resistance. Testing of earth resistance is discussed in more detail later in this paper.

It is easier to see which dimensions of the earth electrode will have a greater impact on the electrode resistance, if we consider what happens to the area of the hemispherical sheaths. In Figure 2, we see that when the electrode is made longer, the area increases significantly. Hence 1/A reduces giving us a reduction in the ground resistance. However, if the diameter of the ground rod is increased, this offers very little change in the area of the hemispherical shells and hence little changes in the resistance.

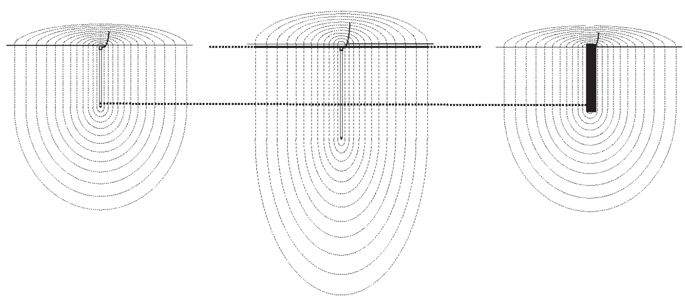


Figure 2: Effect of Longer and Deeper Ground Rods on Ground Resistance

Ground Electrode Design Principles and Testing

This intuitive understanding can be extended to horizontal electrodes. It can be seen in Figure 3 that making a horizontal electrode longer will increase the surface area of the sheaths surrounding it. Hence longer electrodes rather than deeper electrodes, will give a greater reduction in the electrode resistance.

Another factor that will have an impact on the ground resistance is the conductivity or the resistivity of the soil. In fact it is this factor that makes it impossible to have a "one size fit all" grounding design for different sites.

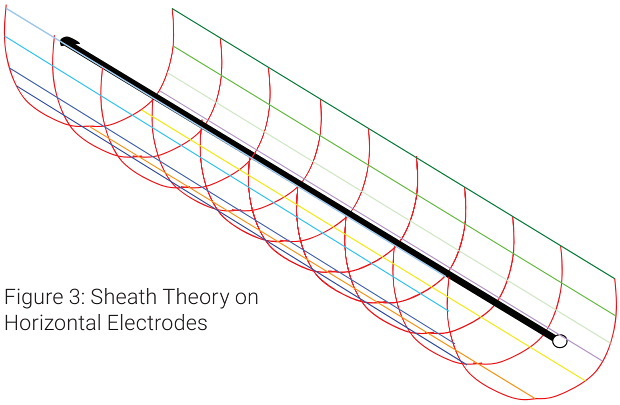


Figure 3: Sheath Theory on Horizontal Electrodes

SOIL RESISTIVITY

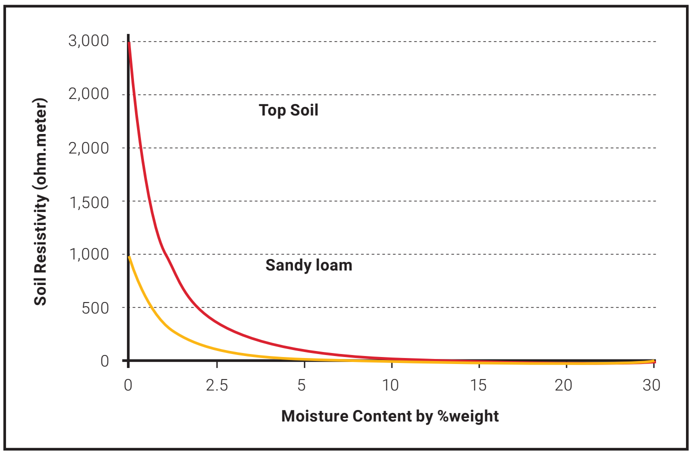
Soil resistivity is another name for the specific resistance of the soil. It is measured in ohm-meters or ohm-centimeters. An ohm-meter is that resistivity of the soil when it has a resistance of 1 ohm between opposite faces of a cube with one meter sides.

Resistance is directly proportional to soil resistivity. This relationship is not as easy to compute in real life as it may sound, because soil resistivity will inevitably vary with depth. The second difficulty in dealing with different locations is that the resistivity varies greatly with sites.

The tables below give an idea of the resistivity of several mediums that are of interest for the design of grounding system.

Material	Typical Resitivity
Copper	1.72 x 10-8 ohm.m
GEM, Material	0.12 ohm.m
Bentonite	2.5 ohm.m
Concrete	30 to 90 ohm.m

Factors that will affect the resistivity of the soil are the soil type, compactness, chemical composition, temperature and water content. Figure 4 shows the effect of moisture content and temperature on soil resistivity.



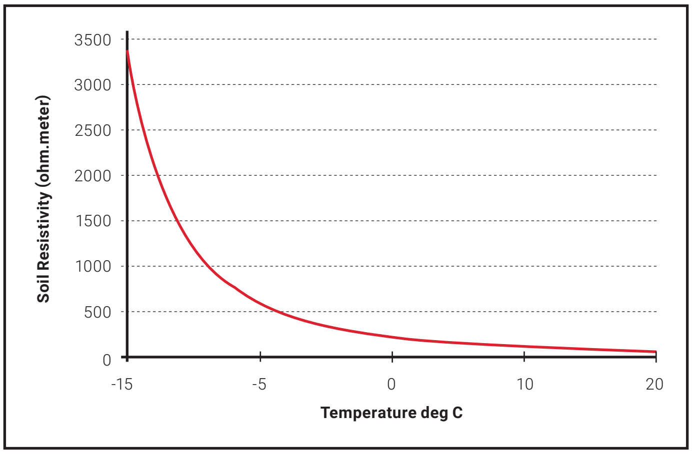


Figure 4: Effect of moisture content and temperature on the soil resistivity

Ground Electrode Design Principles and Testing

MEASUREMENT OF SOIL RESISTIVITY

There are several methods of measuring the soil resistivity.

These include:

• Wenner Array 4-Point Method

• Schlumberger Array

• Driven Rod Method

The Wenner Array method is discussed in this paper because this is the most common method of measuring soil resistivity. The scope of this document does not allow detailed discussion on other soil testing methods.

Using the Wenner Array method, four small electrodes (auxiliary probes) are placed in a straight line at intervals of a, to a depth of b. A current is passed through the outer two probes, and the potential voltage is then measured between the two inner probes. A simple Ohm's Law equation determines the resistance. From this information, it is now possible to calculate the resistivity of the local soil. For most practical circumstances, "a" is 20 times larger than "b", where we can then make the assumption that b=0.

Then the Resistivity, ρ, is given by:

$$\rho = 2 \pi a Re$$

where

ρ = Resistivity of the local soil (Ω-m)

a = distance between probes (m)

b = depth of probes into the ground (m)

Re = resistance value measured by the testing device (Ω)

These values give an average resistivity of the soil to a depth a. It is recommended that a series of readings be taken at different values of a, as well as in a 90o turned axis. It is a good practice to tabulate or plot the results because that gives a good idea of how the resistivity is changing with depth and will give us a better clue on the type of ground electrode to design.

For example, if the resistivity is very high at the top three meters but drastically drops after that depth, then one would consider designing using electrodes that are driven or drilled to deeper than three meters. Conversely if the resistance does not improve beyond a certain depth, say two meters, then horizontal electrodes may be considered in the ground electrode design.

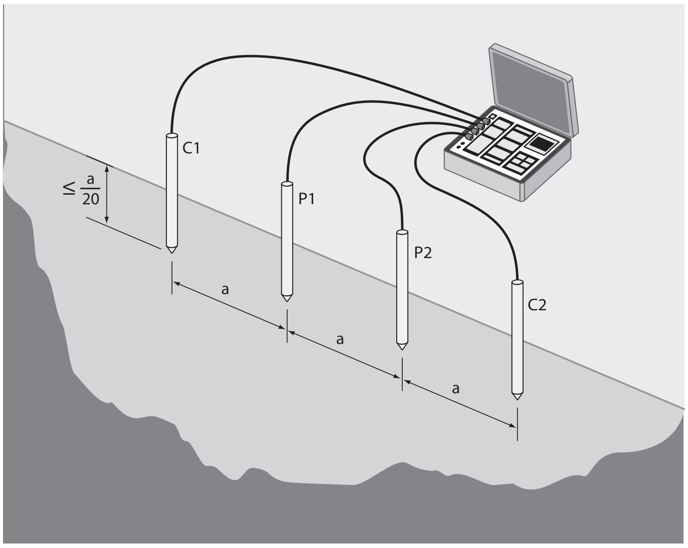


Figure 5: Wenner Array (4 Point Method)

Figure 6 shows a typical record sheet for resistivity measurements. Experience has shown that many testers of the soil resistivity often do not have a full appreciation of the extent to which the test needs to be carried out. It is often noted that only a single or a handful of values are measured. It is recommended that for the design of ground electrode, a comprehensive set of results be gathered in the range of 2–40 meters.

Spacing a	Measured Value of Re	Resistivity R = 2 π a Re
2		
4		
6		
8		
10		

Figure 6: Typical Test Record Sheet for Wenner Array Method

CALCULATING ON GROUND ELECTRODE RESISTANCE OF A SINGLE ROD

The ground resistance can either be calculated using empirical formulae, by using nomograms or by the use of software.

Examples of formulae that are available for use are contained in AS1768 Lightning Protection Standard, Appendix C. The formulae enlisted below, extracted from AS1768, are two most commonly used.

a) Single vertical rod length *L* and diameter *d* meters, top of rod level with surface:

$$R = \frac{\rho}{2\pi L}\left[\ln\left(\frac{8L}{d}\right) - 1\right] \qquad \text{... C3(1)}$$

Where

R = resistance, ohms

ρ = soil resistivity, in ohm meters

L = buried length of grounding electrode, in meters

d = diameter of grounding electrode, in meters

Note: Equation C3(1) is commonly referred to as the 'modified Dwight formula'.

b) Straight horizontal wire of length *L* and diameter *d* meters, on surface:

$$R = \frac{\rho}{\pi L}\left[\ln\left(\frac{4L}{d}\right) - 1\right] \qquad \text{... C3(5)}$$

For a thin strip grounding electrode, the diameter can be replaced with a half-width of the strip.

Traditionally software programs have been able to carry out two layer models of ground resistivity. That means that resistivity measured had to be averaged out to two values with corresponding depths. Modern software can take multi-layer resistivity values as an input.

In fact the real value of the software is not so much in computing resistance values for single or a few electrodes as this can be done easily with a formulae. However they can be powerful in calculating resistance of multiple ground electrodes, step and touch voltages and also simulating fault current injection.

Another method of calculating the resistance of a single ground rod, when the dimensions and the resistivity are known is using nomograms. In the example in Figure 7, a 7m ground rod, of diameter 10mm will produce a resistance of 7.6 ohms if the reading from the Wenner 4-Point test is 1 ohm.

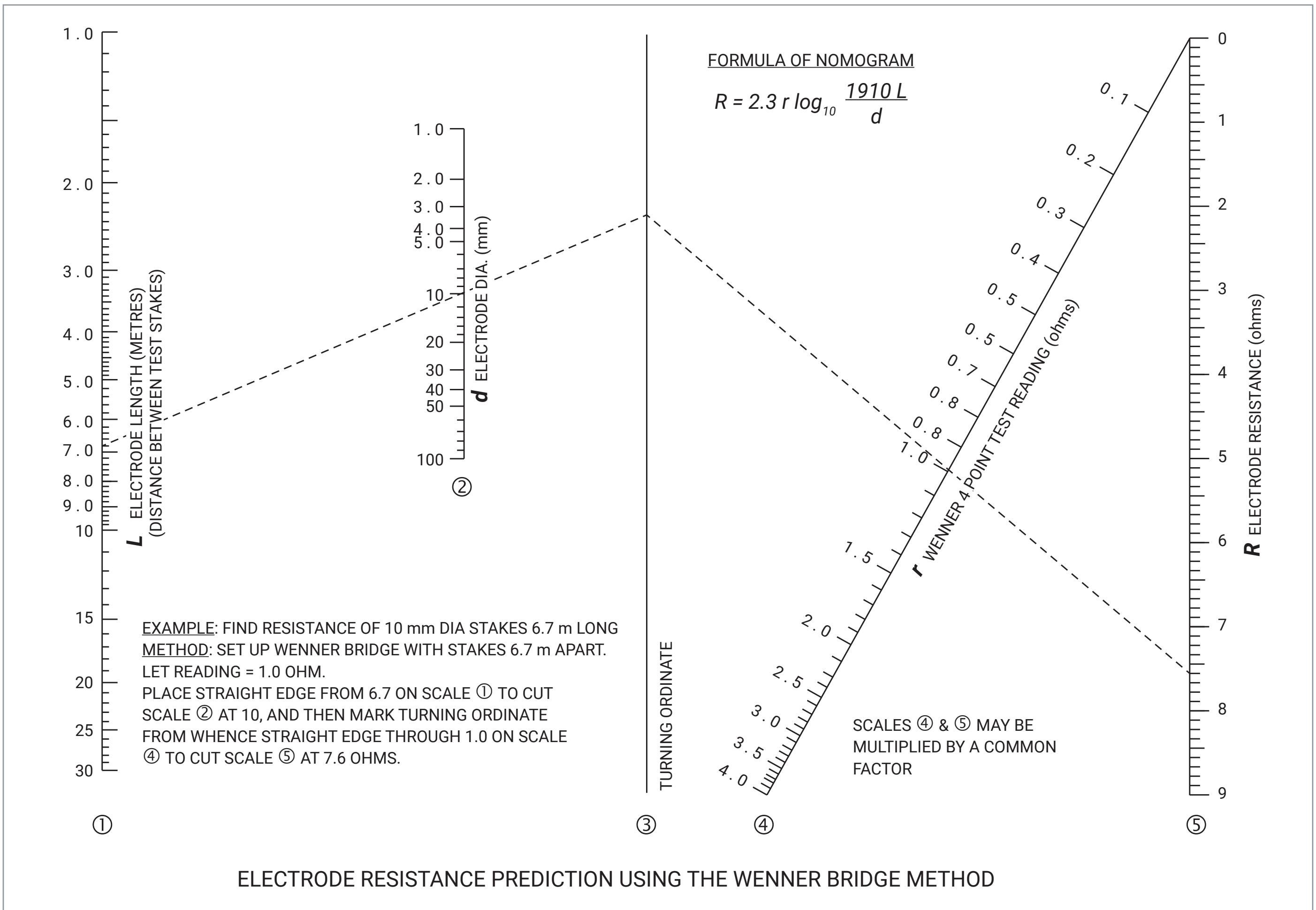


Figure 7: Nomogram to calculate resistance of a single ground rod.

Ground Electrode Design Principles and Testing

CALCULATING ON GROUND ELECTRODE RESISTANCE OF A MULTIPLE GROUND RODS

When ground rods are used in parallel it may seem at first that the resistance could be calculated by the simple equation $1/R = 1/R_1 + 1/R_2 + 1/R_3 ...$

However, when one takes a closer look at the sheath theory discussed earlier, it becomes evident that the spacing between the ground rods may have some impact on the combined resistance. This is because the hemispherical sheaths of each of the electrode will overlap each other and the overlap area has to be compensated for. In the extreme case if two electrodes are superimposed to one another the size of the sheath offered by them will be similar to the sheath offered by one electrode. That is the resistance of two electrodes will be similar to that of one electrode if they are installed totally adjacent.

Rules of thumbs and utilization factors are used in everyday calculations to quickly compute parallel resistances without excessive analysis.

For example, when two electrodes are placed one electrode length apart, 85 percent utilization of their parallel resistance is achieved. When these electrodes are two electrodes apart, 92 percent utilization is achieved. We sometimes see a rule of thumb used in practice that states that the electrode spacing needs to be at least twice the electrode depth, based on this utilization.

Prior to the existence of software to carry out calculations, the use nomograms were the incumbent method of calculating resistance of multiple ground rods. There is no reason that these cannot be used today for quick calculations.

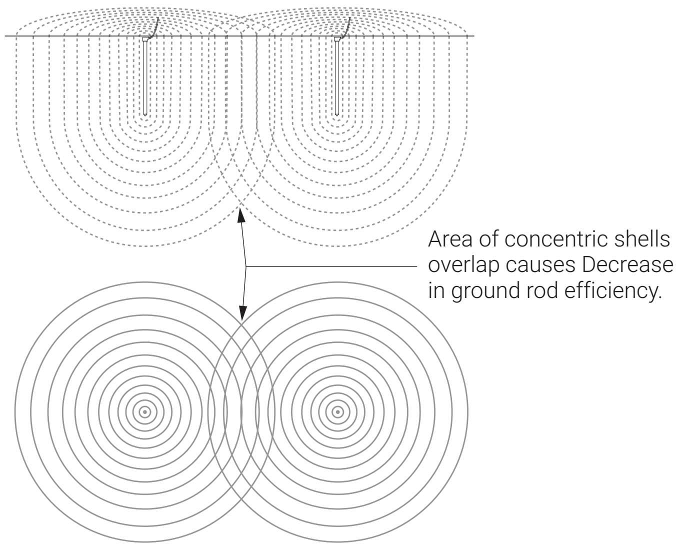


Figure 8: Parallel ground rods

Figure 9 shows a nomogram that can be used to design a multiple electrode system if the resistance of one electrode was known through calculation or measurement.

The calculation of the electrode resistance for a multiple ground rod system is a trivial matter when using modern-day software. It is essentially a matter of inputting the soil resistivity, electrode dimensions and the grid size layout and it will churn out a number, without too much fuss.

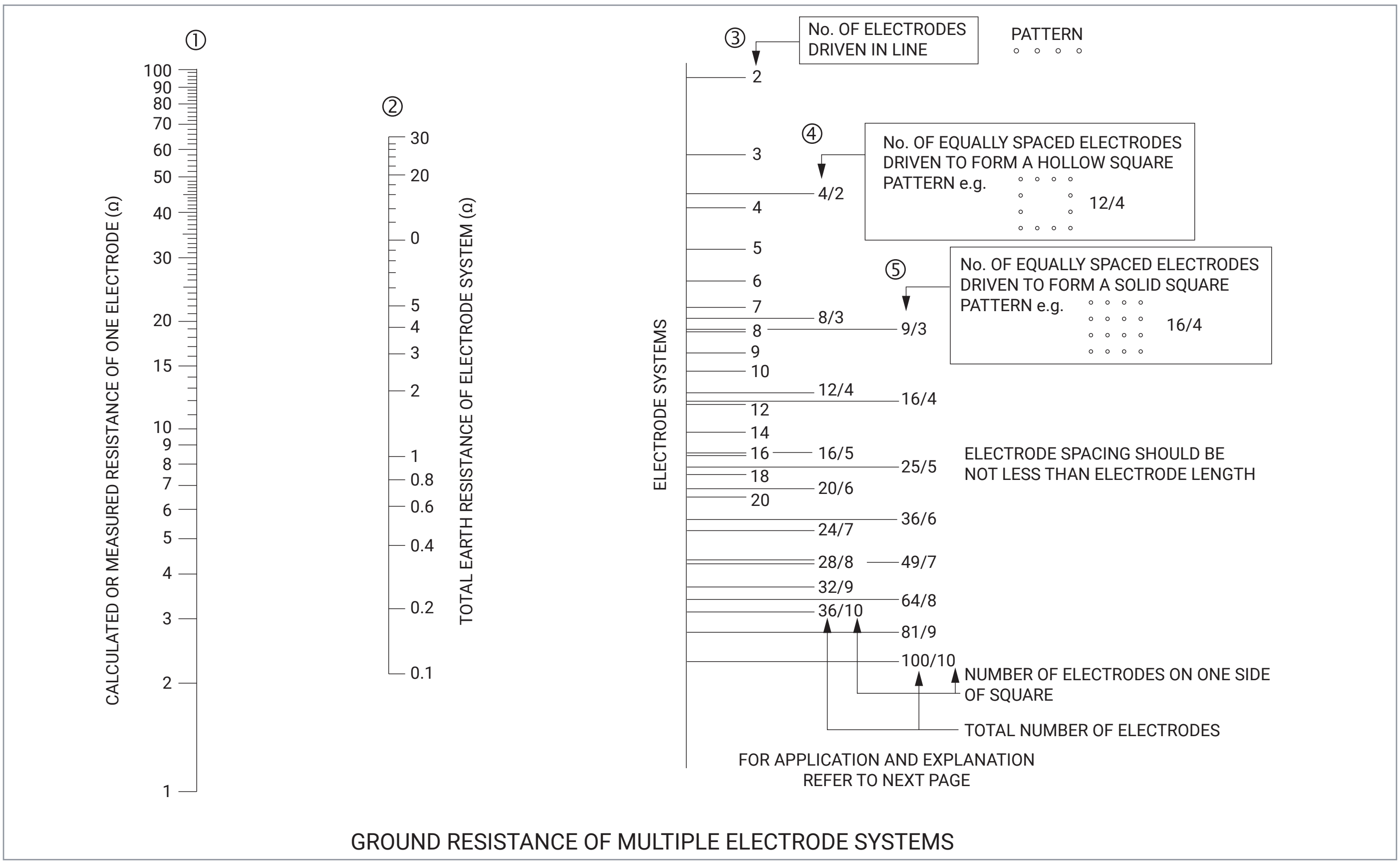


Figure 9: Ground resistance of multiple ground rods

Ground Electrode Design Principles and Testing

MEASUREMENT OF ELECTRODE RESISTANCE

When an electrode system has been designed and installed, it is usually necessary to measure and confirm the ground resistance between the electrode and "true Earth". The most commonly used method of measuring the ground resistance of an ground electrode is the 3-point measuring technique shown in Figure 10. This method is derived from the 4-point method, which is used for soil resistivity measurements.

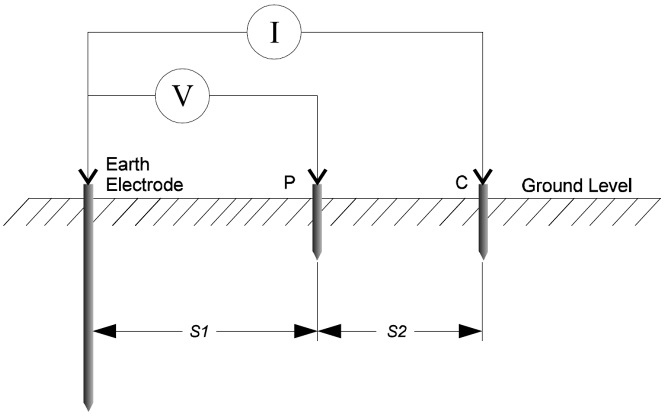


Figure 10: The 3-point method of ground resistance measurement

The 3-point method, called the "fall of potential" method, comprises the ground electrode to be measured and two other electrically independent test electrodes, usually labelled P (Potential) and C (Current). These test electrodes can be of lesser "quality" (higher ground resistance) but must be electrically independent of the electrode to be measured. An alternating current (I) is passed through the outer electrode C and the voltage is measured, by means of an inner electrode P, at some intermediary point between them. The ground resistance is simply calculated using Ohm's Law; Rg = V/I, internally by the test equipment.

When performing a measurement, the aim is to position the auxiliary test electrode C far enough away from the ground electrode under test so that the auxiliary test electrode P will lay outside the effective resistance areas of both the ground system and the other test electrode (see Figure 11).

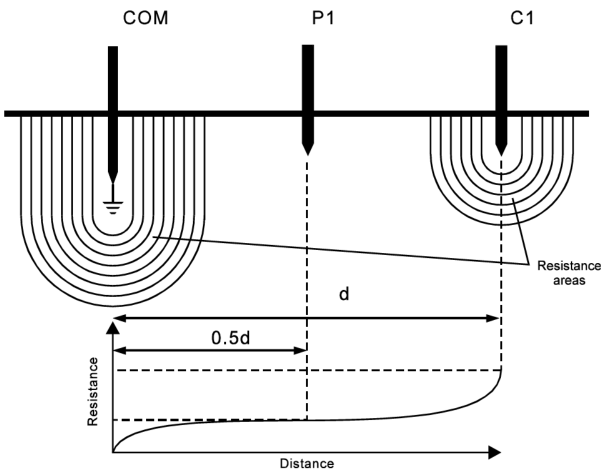


Figure 11: Resistance areas and the variation of the measured resistance with voltage electrode position

If the current test electrode, C, is too close, the resistance areas will overlap and there will be a steep variation in the measured resistance as the voltage test electrode is moved. If the current test electrode is correctly positioned, there will be a 'flat' (or very nearly so) resistance area somewhere in between it and the ground system, and variations in the position of the voltage test electrode should only produce very minor changes in the resistance figure.

The instrument is connected to the ground system under test via a short length of test cable, and a measurement is taken.

Measurement accuracy can be affected by the proximity of other buried metal objects to the auxiliary test electrodes. Objects such as fences and building structures, buried metal pipes or even other grounding systems can interfere with the measurement and introduce errors. Often it is difficult to judge, merely from visual inspection of the site, a suitable location for the tests stakes and so it is always advisable to perform more than one measurement to ensure the accuracy of the test.

Fall of Potential Method

This is one of the most common methods employed for the measurement of ground resistance and is best suited to small systems that don't cover a wide area. It is simple to carry out and requires a minimal amount of calculation to obtain a result.

The outer test electrode, or current test stake, is driven into the ground a good distance away from the ground system. This distance will depend on the size of the system being tested and the inner electrode, or voltage test stake, is then driven into the ground mid-way between the ground electrode and the current test stake, and in a direct line between them.

Maximum dimension across ground system, m	Distance from 'electrical center' of ground system to voltage test stake, m	Minimum distance from 'electrical center' of ground system to current test stake, m
1	15	30
2	20	40
5	30	60
10	43	85
20	60	120
50	100	200
100	140	280

Figure 12: Variation of current and voltage electrode separation with ground grid size

The Fall of Potential method incorporates a check to ensure that the test electrodes are indeed positioned far enough away for a correct reading to be obtained. It is advisable that this check be carried out, as it is really the only way of ensuring a correct result.

To perform a check on the resistance figure, two additional measurements should be made; the first with the voltage test electrode (P) moved 10 percent of the original voltage

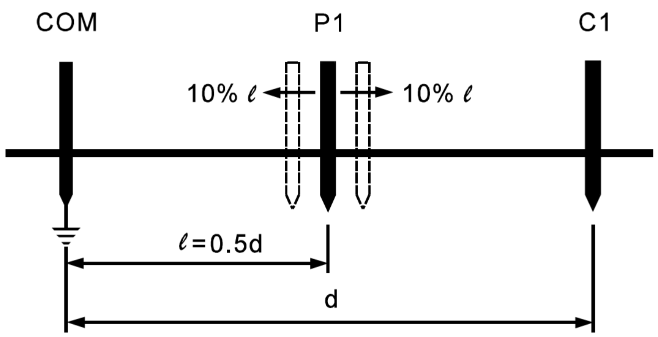


Figure 13: Checking the validity of a resistance measurement

electrode-to-ground system separation away from its initial position, and the second with it moved a distance of 10 percent closer than its original position, as shown in Figure 13.

If these two additional measurements are in agreement with the original measurement, within the required level of accuracy, then the test stakes have been correctly positioned and the DC resistance figure can be obtained by averaging the three results. However, if there is substantial disagreement amongst any of these results, then it is likely that the stakes have been incorrectly positioned, either by being too close to the ground system being tested, too close to one another or too close to other structures that are interfering with the results. The stakes should be repositioned at a larger separation distance or in a different direction and the three measurements repeated. This process should be repeated until a satisfactory result is achieved.

The Slope Method

This method is suitable for use with large grounding systems, such as substation ground. It involves taking a number of resistance measurements at various ground electrode to voltage electrode separations and then plotting a curve of the resistance variation between the ground and the current. From this graph, and from data obtained from the tables, it is possible to calculate the theoretical optimum location for the voltage electrode and thus, from the resistance curve, calculate the true resistance.

It is similar to the fall of potential method but several readings are taken by moving the inner test electrode from very close to the ground grid to the position of the outer test electrode. The readings obtained are then plotted on a graph. Figure 14 shows an example of the graph obtained. It can be observed that at approximately 60 percent of the distance the slope is the gentlest and the resistance corresponding to this is the true resistance of the electrode being measured. In this case it is 20 ohms.

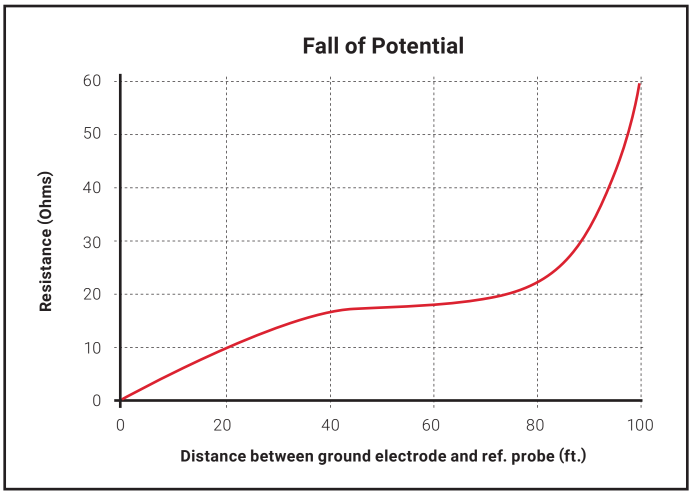


Figure 14: Typical graph, slope

For full details of this method, refer to paper 62975, written by Dr G.F. Tagg, taken from the proceedings of IEEE volume 117, No 11, Nov. 1970.

APPENDIX 1: SAMPLE TEST REPORT – GROUND RESISTANCE

Purpose:	**Measurement of ground resistance at a cell site**		
Date:		Test Equipment Used:	List Brand and Model
Location:		Calibration Date of test Equipment	
Customer:		Tested by:	

Test Procedure:

The ground resistance shall be carried out on the telecommunications ground and the tower ground. The technique used was the Fall of Potential.

The telecommunications earth electrode will consist of a ring grounding system with multiple vertical electrode that will encompass the tower and equipment shelter or cabinet.

When testing the ground resistance, the telecommunications system shall be isolated from connections to AC grounding system, grounding system of collocated carriers, the building, shelter or cabinet, any incoming services and any other objects that are likely to distort the results.

The Fall of Potential Method of Ground Resistance Measurement Method.

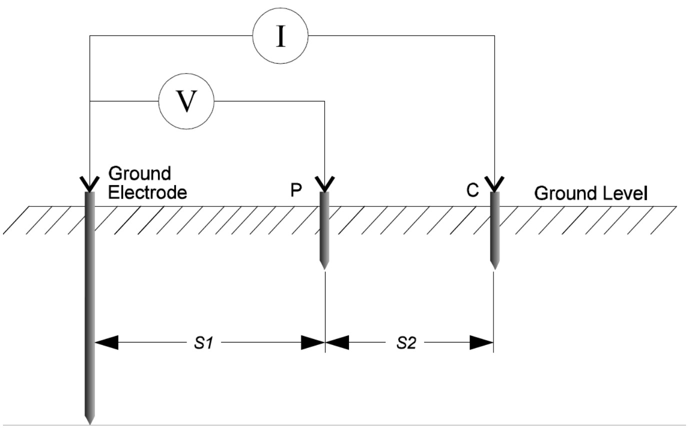


Figure 1.1: Fall of Potential of 3-Point ground resistance testing

The "fall of potential" method, also called the 3-point earth test method comprises the ground electrode to be measured and two other electrically independent test pins, usually labelled P (Potential) and C (Current). These test pins can be of lesser "quality" (higher ground resistance) but must be electrically independent of the electrode to be measured. An alternating current (I) is passed through the outer electrode C and the voltage is measured, by means of an inner electrode P, at some intermediary point between them. The ground resistance is simply calculated using Ohm's Law; Rg = V/I.

The Fall of Potential method incorporates a check to ensure that the test electrodes are indeed positioned far enough away for a correct reading to be obtained. It is advisable that this check be carried, as it is really the only way of ensuring a correct result.

To perform a check on the resistance figure, two additional measurements should be made; the first with the voltage test electrode (P) moved 10 percent of the original voltage electrode-to-ground system separation away from its initial position, and the second with it moved a distance of 10 percent closer than its original position, as shown in Figure 1.2.

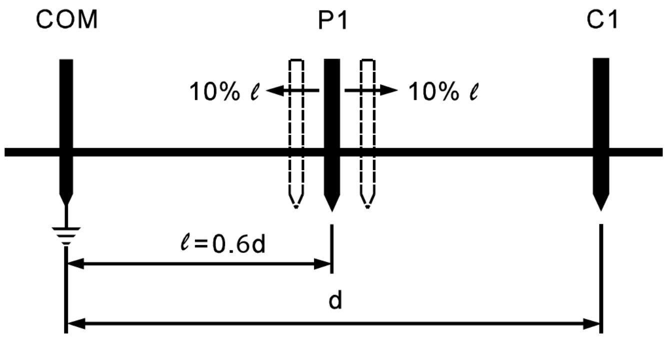


Figure 1.2: Checking the validity of a resistance measurement

If these two additional measurements are in agreement (+/- 5%) with the original measurement, within the required level of accuracy, then the test stakes have been correctly positioned and the ground resistance figure can be obtained by averaging the three results. However, if there is substantial disagreement amongst any of these results, then it is likely that the stakes have been incorrectly positioned, either by being too close to the ground system being tested, too close to one another or too close to other structures that are interfering with the results. The stakes should be repositioned at a larger separation distance or a different direction and the three measurements repeated. This process should be repeated until a satisfactory result is achieved.

The minimum distance d required for ground testing is shown below:

Diagonal Size of ground Ring , DZ	**Distance d**
0-10m	60m
>10m	6 x DZ

Method using a 'dead' ground

The techniques using test spikes explained earlier are the preferred methods of ground testing. In congested areas it may not be possible to find suitable sites for the test spikes, nor sufficient space to run the test leads. In such cases a low resistance conductive water main may be available. This is referred to as a 'dead' ground. Great care must be taken before deciding to adopt this method and its use is not to be encouraged. Before employing this method, the user must be quite sure that no part of the 'dead' ground installation contains plastic or other non-metallic materials.

1) Using a shorting bar supplied, short together terminals 'P2' and 'C2'.

2) Firmly connect a test lead to 'C1' and the other test lead to 'P2' and 'C2'.

3) Firmly connect the free ends of the test leads together as shown in Figure 1.3.

4) Press the 3 pole test push, and take a reading in the normal way.

This test will give the combined resistance to ground of the two grounds in series. If that of the 'dead ground is negligible then the reading may be taken as part of the electrode under test.

The resistence of the two test leads can be found by firmly joining their free ends together, pressing the three pole test push and take the reading in the usual way. Test lead resistance can then be subtracted from the original reading, to obtain the combined resistance of the ground electrode and the 'dead' ground.

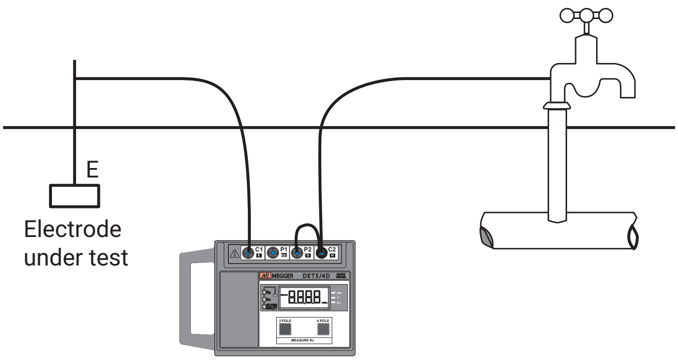


Figure 1.3: 'Dead' ground testing

Test Results:

Ground Resistance Test (Fall of Potential Method)

Diagonal Dimension of ground grid =

d = ... m

Test	Test 1 , ℓ = 0.62d	Test 2, 1, ℓ = 0.62d x 1.1	Test 3, 1, ℓ = 0.62d x 0.9
Resistance Reading			

APPENDIX 2: SAMPLE TEST CERTIFICATE – SOIL RESISTIVITY

Purpose:	**Measurement of Soil Resisivity at Proposed Cell Site**		
Date:		Test Equipment Used:	List Brand and Model
Location:		Calibration Date of test Equipment	
Customer:		Tested by:	
Site Condition: Dry or wet, soil type, any observations that may be important, any observed buried metal nearby, any existence of metallic fence lines nearby			

Test Procedure:

The Wenner method, for soil resistivity testing shall be used. All four electrodes are moved for each test with the spacing between each adjacent pair remaining exactly the same. In each method the depth penetration of the electrodes is less than five percent of the separation to ensure that the approximation of point sources, required by the simplified formulae, remains valid.

For complete procedure, please refer to equipment manual being used.

Two sets of tests shall carried out with a ranging from 1.5 meters up to 9 meters. The results shall be recorded in the result sheet similar below. The test is generally done in two perpendicular directions, but if there are limitations at the site, these can be done in two different directions that are not perpendicular.

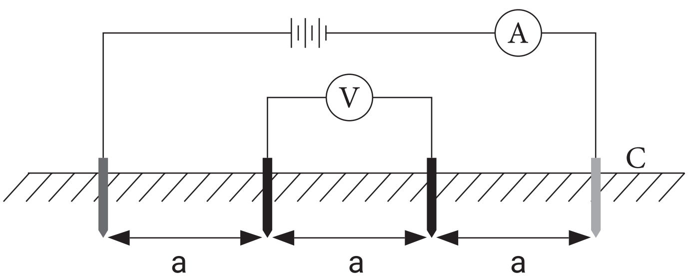


Figure 2.1: Soil resistivity test setup

Test Results

The results obtained are tabulated below.

*The readings shown in yellow are only required if the resistivity measurement at a=9 meters is higher than 400 ohm-m

Spacing a, m	**Measured Value Re1 in Direction 1**	**Measured Value Re2 in Direction 2 (Perpendicular to Direction 1)**	**Average of Re1 and Re2 = Re**	**Resistivity p = 2 π a Re**
1.5				
3.0				
4.5				
6.0				
7.5				
9.0				
10.5*				
12.0*				
13.5*				
15*				

Site Sketch

Sketch the directions the tests were done on the site layout drawings below

Ground Electrode Design Principles and Testing

REFERENCES

1) **AS3015 – 2004**: Electrical installations—Extra-low voltage d.c. power supplies and service grounding within public telecommunications networks
2) **Chris Rempe, ERICO** A Technical Report on The Service Life of Ground Rod Electrodes
3) **Rohit Narayan** Method for the Design of Lightning Protection, Noise Control And Grounding System at a Telecom Facility INTELEC 2014 : Copyright of IEEE
4) **Rohit Narayan** Course Notes, Telecommunications Grounding & Protection
5) **NSW State Electricity Earthing Handbook, 1973.**
6) **Standard IEEE 80, – 2000**: IEEE Guide for Safety in AC Substation Grounding
7) **Standard IEEE 837** IEEE Standard for Qualifying Permanent Connections Used in Substation Grounding
8) **Telecom Training Center Fiji**; Course Notes, Earthing Principles PS001
9) **Earthing Training Manual – ERICO 2001**
10) **Elvis R. Sverko ERICO, Inc. Facility Electrical Protection**, GROUND MEASURING TECHNIQUES: ELECTRODE RESISTANCE TO REMOTE EARTH & SOIL RESISTIVITY U.S.A. Revision Date: February 11, 1999

IMAGE REFERENCES

1) New South Wales Government, Energy Authority of N.S.W., Earthing Handbook
2) Megger DET5/4R & DET5/4D Digital Earth Testers User Guide
3) Paper 62975, written by Dr G.F. Tagg, taken from the proceedings of IEEE volume 117, No 11, Nov. 1970
4) Fundamentals of Ground Electrode Design Author : Rohit Narayan, nVent ERICO, Published in Industrial Electrix magazine Australia, 2007
5) Earthing Fundamental course notes, Telecommunication Training Center, Telecom Fiji Limited, Rohit Narayan 1994
6) Telecommunications Course Notes, Rohit Narayan, nVent ERICO 2014- 2019
7) Paper 62975, written by Dr G.F. Tagg, taken from the proceedings of IEEE volume 117, No 11, Nov. 1970

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