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UNDERSTANDING GROUND RESISTANCE TESTING SOIL RESISTIVITY

Why Measure Soil Resistivity?

Soil resistivity measurements have a threefold purpose. First, such data are used to make sub-surface geophysical surveys as an aid in identifying ore locations, depth to bedrock and other geological phenomena. Second, resistivity has a direct impact on the degree of corrosion in underground pipelines. A decrease in resistivity relates to an increase in corrosion activity and therefore dictates the protective treatment to be used. Third, soil resistivity directly affects the design of a grounding system, and it is to that task that this discussion is directed. When designing an extensive grounding system, it is advisable to locate the area of lowest soil resistivity in order to achieve the most economical grounding installation.

Effects of Soil Resistivity on Ground Electrode Resistance

Soil resistivity is the key factor that determines what the resistance of a grounding electrode will be, and to what depth it must be driven to obtain low ground resistance. The resistivity of the soil varies widely throughout the world and changes seasonally. Soil resistivity is determined largely by its content of electrolytes, which consist of moisture, minerals and dissolved salts. A dry soil has high resistivity if it contains no soluble salts (Figure 1).

	Resistivity (approx), Ω-cm		
Soil	**Min.**	**Average**	**Max.**
Ashes, cinders, brine, waste	590	2,370	7,000
Clay, shale, gumbo, loam	340	4,060	16,300
Same, with varying proportions of sand and gravel	1,020	15,800	135,000
Gravel, sand, stones with little clay or loam	59,000	94,000	458,000

FIGURE 1

Factors Affecting Soil Resistivity

Two samples of soil, when thoroughly dried, may in fact become very good insulators having a resistivity in excess of 10^9 ohm-centimeters. The resistivity of the soil sample is seen to change quite rapidly until approximately 20% or greater moisture content is reached (Figure 2).

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Moisture content	Resistivity Ω-cm	
% by weight	Top soil	Sandy loam
0	>10^9	>10^9
2.5	250,000	150,000
5	165,000	43,000
10	53,000	18,500
15	19,000	10,500
20	12,000	6,300
30	6,400	4,200

FIGURE 2

The resistivity of the soil is also inflenced by temperature. Figure 3 shows the variation of the resistivity of sandy loam, containing 15.2% moisture, with temperature changes from 20° to -15°C. In this temperature range the resistivity is seen to vary from 7200 to 330,000 ohm-centimeters.

Temperature		Resistivity
C	F	Ohm-cm
20	68	7,200
10	50	9,900
0	32 (water)	13,800
0	32 (ice)	30,000
-5	23	79,000
-15	14	330,000

FIGURE 3

Because soil resistivity directly relates to moisture content and temperature, it is reasonable to assume that the resistance of any grounding system will vary throughout the different seasons of the year. Such variations are shown in Figure 4. Since both temperature and moisture content become more stable at greater distances below the surface of the earth, it follows that a grounding system, to be most effective at all times, should be constructed with the ground rod driven down a considerable distance below the surface of the earth. Best results are obtained if the ground rod reaches the water table.

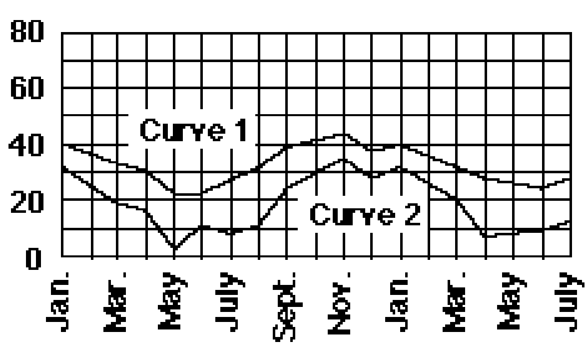

FIGURE 4

Seasonal variation of earth resistance with an electrode of 3/4 inch pipe in rather stony clay soil. Depth of electrode in earth is 3 ft for Curve 1, and 10 ft for Curve 2

In some locations, the resistivity of the earth is so high that low-resistance grounding can be obtained only at considerable expense and with an elaborate

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grounding system. In such situations, it may be economical to use a ground rod system of limited size and to reduce the ground resistivity by periodically increasing the soluble chemical content of the soil. Figure 5 shows the substantial re- duction in resistivity of sandy loam brought about by an increase in chemical salt content.

THE EFFECT OF SALT* CONTENT ON THE RESISTIVITY OF SOIL (Sandy loam, Moisture content, 15% by weight, Temperature,17°C)	
Added Salt (% by weight of moisture)	Resistivity (Ohm-centimeters)
0	10,700
0.1	1,800
1.0	460
5	190
10	130
20	100

FIGURE 5

Chemically treated soil is also subject to considerable variation of resistivity with temperature changes, as shown in Figure 6. If salt treatment is employed, it is necessary to use ground rods which will resist chemical corrosion.

*Such as copper sulfate, sodium carbonate, and others.

THE EFFECT OF TEMPERATURE ON THE RESISTIVITY OF SOIL CONTAINING SALT* (Sandy loam, 20% moisture. Salt 5% of weight of moisture)	
Temperature (Degrees C)	Resistivity (Ohm-centimeters)
20	110
10	142
0	190
-5	312
-13	1,440

FIGURE 6

Salts must be EPA or local ordinance approved prior to use.

SOIL RESISTIVITY MEASUREMENTS
(4-Point Measurement)

Resistivity measurements are of two types; the 2-point and the 4-point method. The 2-point method is simply the resistance measured between two points. For most applications the most accurate method is the 4-point method which is used in the Model 4610 or Model 4500 Ground Tester. The 4-point method (Figures 7 and 8), as the name implies, requires the insertion of four equally spaced and in-line electrodes into the test area. A known current from a constant current generator is passed between the outer electrodes. The potential drop (a function of the resistance) is then measured across the two inner electrodes. The Model 4610 and Model 4500 are calibrated to read directly in ohms.

$$\rho = \frac{4\pi AR}{1 + \dfrac{2A}{\sqrt{(A^2 + 4B^2)}} - \dfrac{2A}{\sqrt{(4A^2 + 4B^2)}}}$$

Where: A = distance between the electrodes in centimeters
B = electrode depth in centimeters

If A > 20 B, the formula becomes:

$\rho = 2\pi AR$ **(with A in cm)**
$\rho = 191.5\ AR$ **(with A in feet)**
ρ **= Soil resistivity (ohm-cm)**

This value is the average resistivity of the ground at a depth equivalent to the distance "A" between two electrodes.

Soil Resistivity Measurements with the Model 4500

Given a sizable tract of land in which to determine the optimum soil resistivity some intuition is in order. Assuming that the objective is low resistivity, preference should be given to an area containing moist loam as opposed to a dry sandy area. Consideration must also be given to the depth at which resistivity is required.

Example

After inspection, the area investigated has been narrowed down to a plot of ground approximately 75 square feet (7 m²). Assume that you need to determine the resistivity at a depth of 15 feet (450 cm). The distance "A" between the electrodes must then be equivalent to the depth at which average resistivity is to be determined (15 ft, or 450 cm). Using the more simplified Wenner formula ($\rho = 2\pi AR$), the electrode depth must then be 1/20th of the electrode spacing or 8-7/8" (22.5 cm).

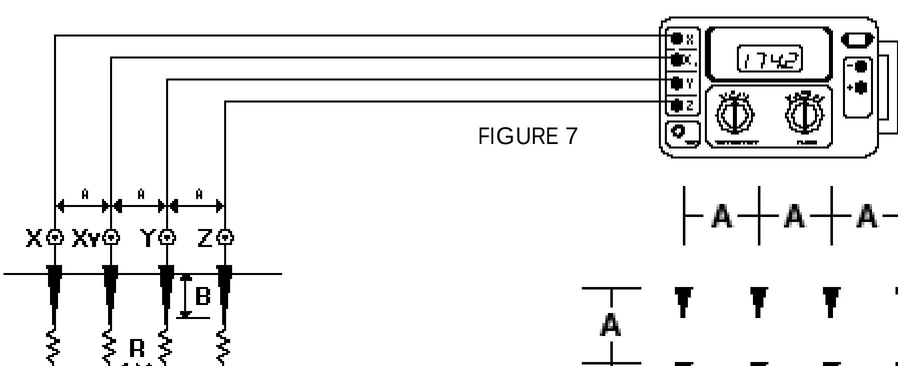

FIGURE 7

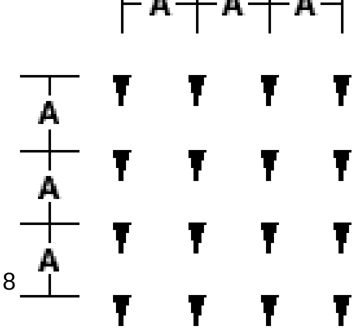

FIGURE 8

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Lay out the electrodes in a grid pattern and connect to the Model 4500 as shown in Figure 8. Proceed as follows:

- Remove the shoring link between X and Xv (C1, P1)
- Connect all four auxiliary rods (Figure 7)

For example, if the reading is R = 15

ρ (resistivity) = 2π x A x R
A (distance between electrodes) = 450 cm
ρ = 6.28 x 15 x 450 = 42,390 Ω-cm

GROUND ELECTRODES

The term "ground" is defined as a conducting connection by which a circuit or equipment is connected to the earth. The connection is used to establish and maintain as closely as possible the potential of the earth on the circuit or equipment connected to it. A "ground" consists of a grounding conductor, a bonding connector, its grounding electrode(s), and the soil in contact with the electrode.

Grounds have several protection applications. For natural phenomena such as lightning, grounds are used to discharge the system of current before personnel can be injured or system components damaged. For foreign potentials due to faults in electric power systems with ground returns, grounds help ensure rapid operation of the protection relays by providing low resistance fault current paths. This provides for the removal of the foreign potential as quickly as possible. The ground should drain the foreign potential before personnel are injured and the power or communications system is damaged.

Ideally, to maintain a reference potential for instrument safety, protect against static electricity and limit the system to frame voltage for operator safety, a ground resistance should be zero ohms. In reality, as we describe further in the text, this value cannot be obtained.

Last but not least, low ground resistance is essential to meet NEC®, OSHA and other electrical safety standards.

Figure 9 illustrates a grounding rod. The resistance of the electrode has the following components:

(A) the resistance of the metal and that of the connection to it.
(B) the contact resistance of the surrounding earth to the electrode.
(C) the resistance in the surrounding earth to current flow or earth resistivity which is often the most significant factor.

More specifically:

(A) Grounding electrodes are usually made of a very conductive metal (copper or copper clad) with adequate cross sections so that the overall resistance is negligible.

(B) The National Institute of Standards and Technology has demonstrated that the resistance between the electrode and the surrounding earth is negligible if the electrode is free of paint, grease, or other coating, and if the earth is firmly packed.

(C) The only component remaining is the resistance of the surrounding earth. The electrode can be thought of as being surrounded by concentric shells of earth or soil, all of the same thickness. The closer the shell to the electrode, the smaller its surface; hence, the greater its resistance. The farther away the shells are from the electrode, the greater the surface of the shell; hence, the lower the resistance. Eventually, adding shells at a distance from the grounding electrode will no longer noticeably affect the overall earth resistance surrounding the electrode. The distance at which this effect occurs is referred to as the effective resistance area and is directly dependent on the depth of the grounding electrode.

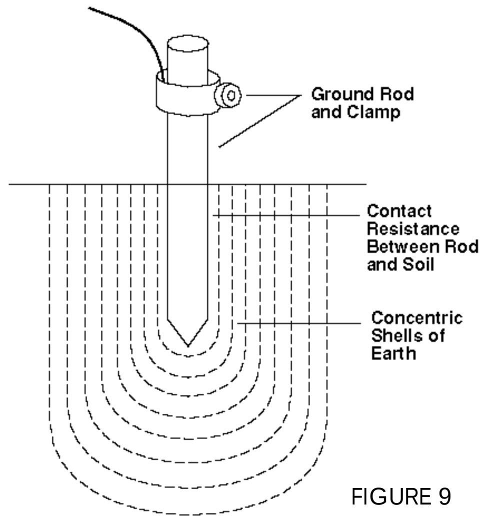

FIGURE 9

In theory, the ground resistance may be derived from the general formula:

$$R = \frac{\rho L}{A} \qquad \text{Resistance} = \text{Resistivity} \times \frac{\text{Length}}{\text{Area}}$$

This formula illustrates why the shells of concentric earth decrease in resistance the farther they are from the ground rod:

$$R = \text{Resistivity of Soil} \times \frac{\text{Thickness of Shell}}{\text{Area}}$$

In the case of ground resistance, uniform earth (or soil) resistivity throughout the volume is assumed, although this is seldom the case in nature. The equations for systems of electrodes are very complex and often expressed only as approximations. The most commonly used formula for single ground electrode systems, developed by Professor H. R. Dwight of the Massachusetts Institute of Technology, is the following:

$$R = \frac{\rho}{2\pi L} \times \frac{\{(\ln 4L) - 1\}}{r}$$

R = resistance in ohms of the ground rod to the earth (or soil)
L = grounding electrode length
r = grounding electrode radius
ρ = average resistivity in ohms-cm.

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Effect of Ground Electrode Size and Depth on Resistance

Size: **Increasing the diameter of the rod does not materially reduce its resistance. Doubling the diameter reduces resistance by less than 10% (Figure 10).**

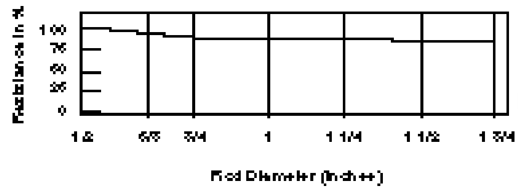

FIGURE 10

Depth: As a ground rod is driven deeper into the earth, its resistance is substantially reduced. In general, doubling the rod length reduces the resistance by an additional 40% (Figure 11). The NEC (1987, 250-83-3) requires a minimum of 8 ft (2.4 m) to be in contact with the soil. The most common is a 10 ft (3 m) cylindrical rod which meets the NEC code.A minimum diameter of 5/8 inch (1.59 cm) is required for steel rods and 1/2 inch (1.27 cm) for copper or copper clad steel rods (NEC 1987, 250-83-2). Minimum practical diameters for driving limitations for 10 ft (3 m) rods are:

- **1/2 inch (1.27 cm) in average soil**
- **5/8 inch (1.59 cm) in moist soil**
- **3/4 inch (1.91 cm) in hard soil or more than 10 ft driving depths**

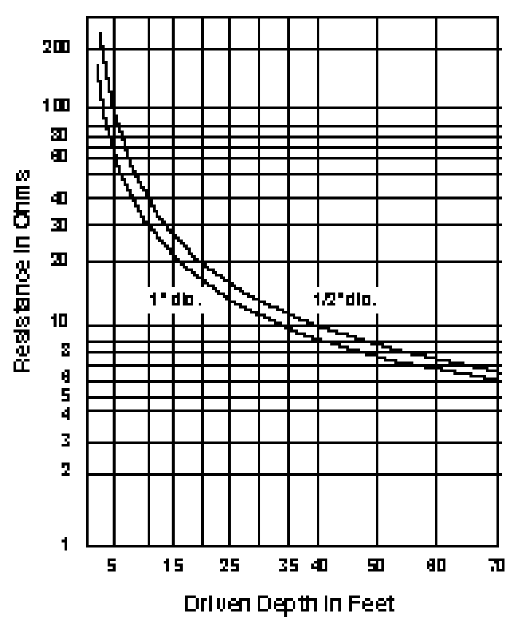

FIGURE 11

Ground Resistance Versus Ground Rod Depth

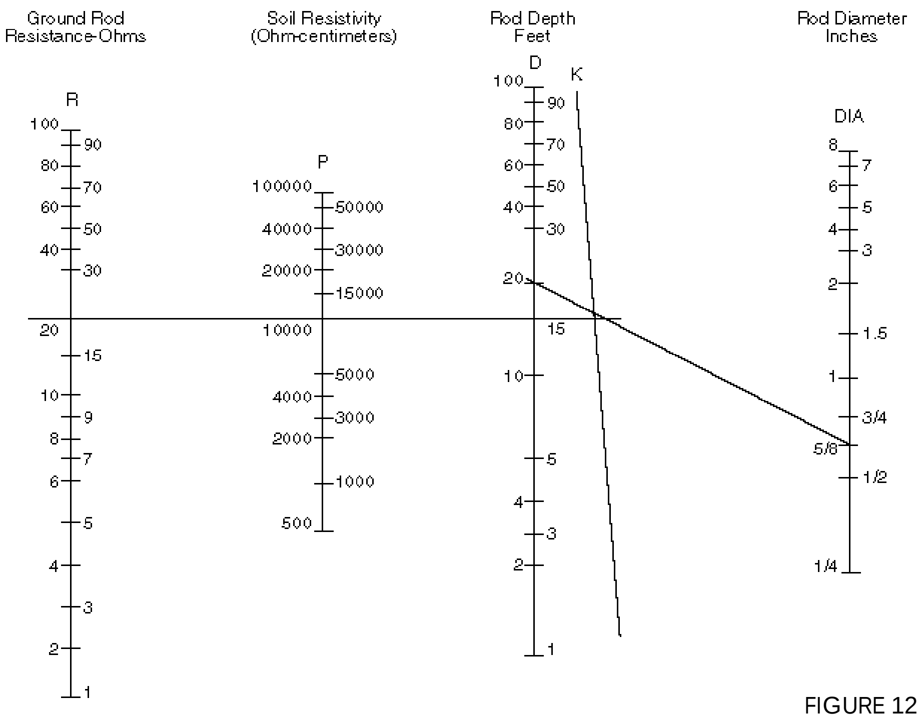

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FIGURE 12

Grounding Nomograph

1. Select required resistance on R scale.
2. Select apparent resistivity on P scale.
3. Lay straightedge on R and P scale, and allow to intersect with K scale.
4. Mark K scale point.
5. Lay straightedge on K scale point & DIA scale, and allow to intersect with D scale.
6. Point on D scale will be rod depth required for resistance on R scale.

GROUND RESISTANCE VALUES

NEC® 250-84 (1987): Resistance of man-made electrodes:

"A single electrode consisting of a rod, pipe, or plate which does not have a resistance to ground of 25 ohms or less shall be augmented by one additional rod of any of the types specified in section 250-81 or 250-83. Where multiple rod, pipe or plate electrodes are installed to meet the requirements of this section, they shall be not less than 6 ft (1.83 m) apart."

The National Electrical Code® (NEC) states that the resistance to ground shall not exceed 25 ohms. This is an upper limit and guideline, since much lower resistance is required in many instances.

"How low in resistance should a ground be?" An arbitrary answer to this in ohms is difficult. The lower the ground resistance, the safer; and for positive protection of personnel and equipment, it is worth the effort to aim for less than one ohm. It is generally impractical to reach such a low resistance along a distribution system or a transmission line or in small substations. In some

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regions, resistances of 5 ohms or less may be obtained without much trouble. In other regions, it may be dificult to bring resistance of driven grounds below 100 ohms.

Accepted industry standards stipulate that transmission substations should be designed not to exceed 1Ω. In distribution substations, the maximum recommended resistance is for 5 ohms or even 1 ohm. In most cases, the buried grid system of any substation will provide the desired resistance.

In light industrial or in telecommunication central offices, 5Ω is often the accepted value. For lightning protection, the arrestors should be coupled with a maximum ground resistance of 1Ω.

These parameters can usually be met with the proper application of basic grounding theory. There will always exist circumstances which will make it difficult to obtain the ground resistance required by the NEC® or other safety standards. When these situations develop, several methods of lowering the ground resistance can be employed. These include parallel rod systems, deep driven rod systems utilizing sectional rods, and chemical treatment of the soil. Additional methods discussed in other published data are buried plates, buried conductors (counterpoise), electrically connected building steel, and electrically connected concrete reinforced steel.

Electrically connecting to existing water and gas distribution systems was often considered to yield low ground resistance; however, recent design changes utilizing non-metallic pipes and insulating joints have made this method of obtaining a low resistance ground questionable and in many instances unreliable.

The measurement of ground resistances may only be accomplished with specially designed test equipment. Most instruments use the fall-of-potential principle of alternating current (AC) circulating between an auxiliary electrode and the ground electrode under test. The reading will be given in ohms, and represents the resistance of the ground electrode to the surrounding earth. AEMC has also recently introduced clamp-on ground resistance testers.

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