"Getting down to earth..."

A Manual on

EARTH-RESISTANCE TESTING

for the practical man

- Electrical grounding systems
- Earth resistivity

FOURTH EDITION
APRIL 1981

James G. Biddle INSTRUMENTS
510 Township Line Road, Blue Bell, Pennsylvania 19422

ONE DOLLAR PER COPY

A DOWN-TO-EARTH SUBJECT . . .
VITAL TO INDUSTRY AND SCIENCE

Nothing is quite so common or abundantly available throughout the world as the earth's soil. We're more apt to think of earth as something to be tilled for planting, or to be excavated for a building foundation. Yet, it also has an electrical property —conductivity (or low resistance)—that is being put to very practical use every day in industrial plants and utilities.

Broadly speaking, "earth resistance" is the resistance of soil to the passage of electric current. Actually, the earth is a relatively poor conductor of electricity compared to normal conductors like copper wire. But, if the area of a path for current is large enough, resistance can be quite low and the earth can be a good "conductor."

Measurement of earth resistance is made in two ways for two important fields of use:

1. Determining the effectiveness of "ground" grids and connections which are used with electrical systems to protect personnel and equipment.
2. Prospecting for good (low resistance) "ground" locations, or obtaining measured resistance values which can give specific information about what lies some distance below the earth's surface (such as depth to bed rock).

It is not the intent of this manual to go too deeply into the theory and mathematics of the subject. As covered in the references at the end, there are many excellent books and papers that cover these. Rather, the coverage herein is in simple language for easy understanding by the user in industry.

From years of experience in supplying instruments for the tests involved, James G. Biddle Co. can provide much practical advice to help you make specific tests and will be pleased to have a representative call on you to discuss your problem. For this free service, or copies of literature, simply use one of the postpaid cards included in the back of this manual.

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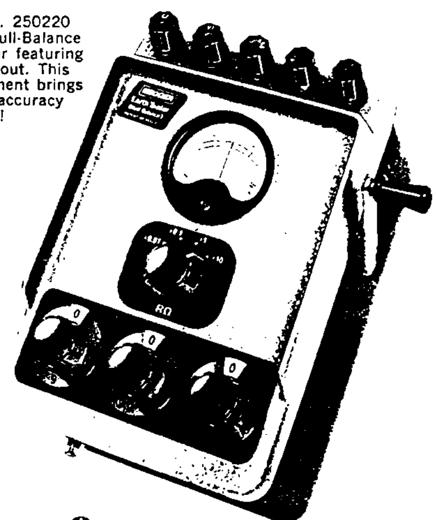
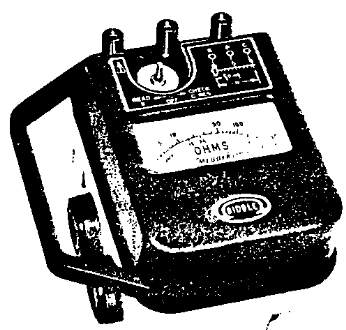
Catalog No. 250220 Megger® Null-Balance Earth Tester featuring in-line readout. This fine instrument brings laboratory accuracy to the field!





The Catalog No. 250260 Megger Direct-Reading Earth Tester; a compact, easy-to-use instrument for single rod or small ground system tests.

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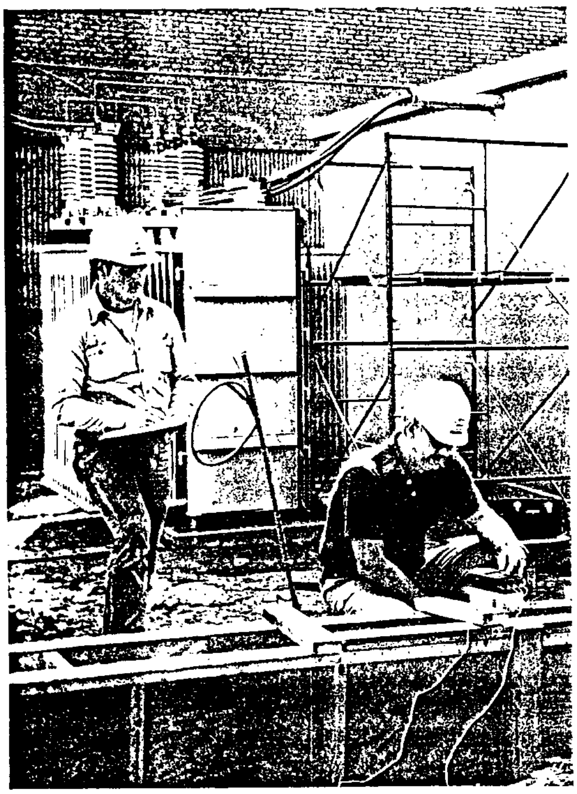


Checking the earth-resistance of a grounding system at a substation.

SECTION I

Measuring Earth Resistance For Electrical Grounding Systems

The simplest and somewhat misleading idea of a good "ground" for an electrical system is a section of iron pipe driven into the earth with a wire conductor connected from the pipe to the electrical circuit (Fig. 1). This may, or may *not*, be a suitable low resistance path for electric current to protect personnel and equipment.

A *practical* earth electrode that provides a low ground resistance is not always easy to obtain. But from experience gained by others you can learn how to set up a reliable system and how to check the resistance value with reasonable accuracy. As you will see, earth resistivity (Part II) has an important bearing on electrode resistance, as does the depth, size, and shape of the electrode.

The principles and methods of *earth-resistance testing* covered in this section apply to lightning arrester installations as well as to other systems that require low-resistance ground connections. Such tests are made in power-generating stations, electrical-distribution systems, industrial plants, and telecommunication systems.

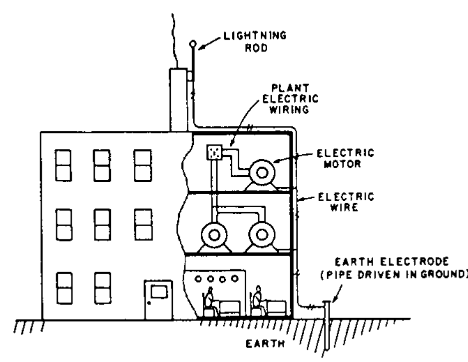


Fig. 1—A simplified grounding system in an industrial plant.

THREE FACTORS THAT CAN CHANGE YOUR "MINIMUM" EARTH RESISTANCE

We will discuss later what value of earth resistance is considered low enough. You'll see that there's no general rule usable for all cases. First, however, consider three factors that can *change* the earth electrode requirements from year to year:

1. A plant or other electrical facility can expand in size. Also, new plants continue to be built larger and larger. Such changes create different needs in the earth electrode. What was formerly a suitably low earth resistance can become an obsolete "standard."

2. As more non-metallic pipes and conduits are installed underground, such installations become less and less dependable as effective, low-resistance ground connections.

3. In many locations, the water table is gradually falling. In a year or so, earth electrode systems that formerly were effective may end up in dry earth of high-resistance.

These factors emphasize the importance of a continuous, periodic program of earth-resistance testing. It is not enough to check the earth resistance only at the time of installation.

SOME BASIC DEFINITIONS

First, let's define our terms. As early as 1918*, the terms *ground, permanent ground,* and *ground connections* were defined to mean "electrical connections intentionally made between electrical bodies (or conducting bodies in close proximity to electrical circuits) and metallic bodies in the earth—such as rods, water pipes, plates, or driven pipes."

The *metallic body* in the earth is often referred to as an *electrode* even though it may be a water-pipe system, buried strips or plates, or wires. Such combinations of metallic bodies are called a *grid.* The *earth resistance* we're concerned with is the resistance to current from the *electrode* into the surrounding earth.

To appreciate why earth resistance must be low, you need only use Ohm's Law: $E = R \times I$—where E is volts; R, the resistance in ohms; and I, the current in amperes. Assume that you have a 4,000-volt supply (2,300 volts to "ground") with a resistance of 13 ohms (see Fig. 2). Now, assume that an exposed wire in this system touches a motor frame that is connected to a grounding system which has a 10-ohm resistance to earth.

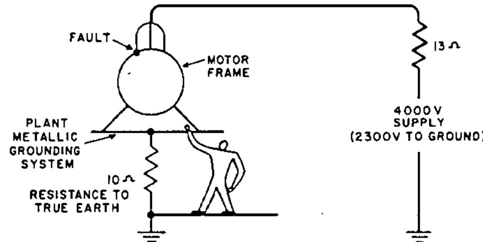


Fig. 2—Example of an electrical circuit with too high an earth resistance.

By Ohm's Law, there will be a current of 100 amperes** through the *fault* (from the motor frame to the earth). If you happen to touch the motor frame and are grounded solidly to earth, (say, by standing in a puddle) you could be subjected to 1,000 volts (10 ohms times 100 amperes).

As you'll note from Point 2, page 11, this may be much more than enough to kill you instantly. If, however, the earth resistance is less than one ohm, the "shock" you'd get would be under 100 volts (1×100) and you'd probably live to correct the fault.

Equipment can also be damaged similarly by overvoltages caused by high-resistance grounding systems.

* Reference 19

** $I = \frac{E}{R} = \frac{2,300}{10 + 13} = 100$ amp.

FACTORS INFLUENCING REQUIREMENTS FOR A GOOD GROUNDING SYSTEM

In an industrial plant or other facility that requires a grounding system, one or more of the following must be carefully considered (See Fig. 3):

1. *Limiting to definite values the voltage to earth of the entire electrical system.* Use of a suitable grounding system can do this by maintaining some point in the circuit at earth potential. Such a grounding system provides these advantages:
   a. Limits voltage to which the system-to-ground insulation is subjected, thereby more definitely fixing the insulation rating.
   b. Limits the system-to-ground or system-to-frame voltage to values safe for personnel.
   c. Provides a relatively stable system with a minimum of transient overvoltages.
   d. Permits any system fault to ground to be quickly isolated.

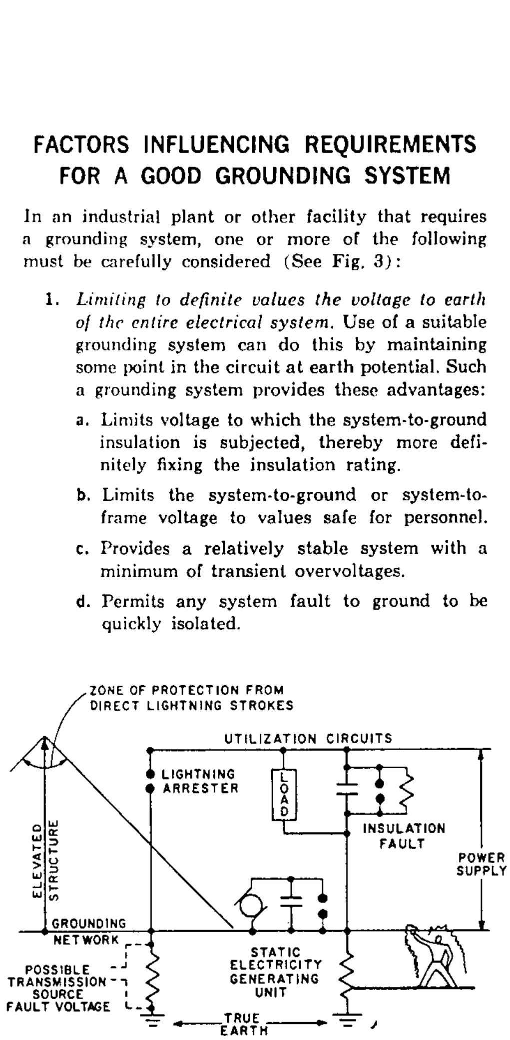


Fig. 3—Typical conditions to be considered in a plant grounding system.

2. *Proper grounding of metallic enclosures and supporting structures* that are part of the electrical system and may be contacted by personnel. Also, to be included are portable electrically-operated devices. Consider that only a small amount of electric current—*as little as 0.1 ampere for one second*—can be fatal! An even smaller amount can cause you to lose muscular control. These low currents can occur in your body at voltages as low as 100 volts, if your skin is moist.
3. *Protection against static electricity from friction.* Along with this are the attendant hazards of shock, fire and explosion. Moving objects that may be inherent insulators—such as paper, textiles, conveyor belts or power belts and rubberized fabrics—can develop surprisingly high charges unless properly grounded.
4. *Protection against direct lightning strokes.* Elevated structures, such as stacks, the building proper, water tanks, etc.—may require lightning rods connected into the grounding system.
5. *Protection against induced lightning voltages.* This is particularly a factor if aerial power distribution and communications circuits are involved. Lightning arresters may be required in strategic locations throughout the plant.
6. *Providing good grounds for electric process control and communication circuits.* With the increased use of industrial control instruments, computers, and communications equipment, accessibility of low-resistance ground connections in many plant locations—in office and production areas—must be considered.

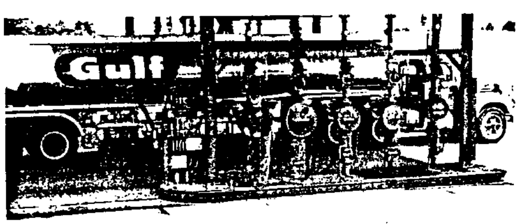
NATIONAL ELECTRICAL CODE MAXIMUM VALUES

The National Electrical Code, Section 250-84 states that a single electrode with a resistance to ground greater than 25 ohms shall be augmented by one additional electrode.

We recommend that single-electrode grounds be tested when installed, and periodically afterward.

We italicized the last phrase because of its importance. Resistance to earth can vary with changes in climate and temperature. Such changes can be considerable. An earth electrode that was good (low-resistance) when installed may not stay that way; to be sure, you must check it periodically.

We cannot tell you what your maximum earth resistance should be. For specific systems in definite locations, specifications are often set. Some call for 5 ohms maximum; others accept no more than 3 ohms. In certain cases, resistances as low as a small fraction of an ohm are required.



Photograph courtesy of Gulf Oil Corp

Megger Null-Balance Earth Tester being used to check grounding system at a Bulk petroleum loading bay.

NATURE OF AN EARTH ELECTRODE

Resistance to current through an earth electrode actually has three components (Fig. 4):

1. Resistance of the electrode itself and connections to it.
2. Contact resistance between the electrode and the soil adjacent to it.
3. Resistance of the surrounding earth.

Electrode Resistance: Rods, pipes, masses of metal, structures, and other devices are commonly used for earth connections. These are usually of sufficient size or cross-section that their resistance is a negligible part of the total resistance.

Electrode-Earth Contact Resistance: This is much less than you might think. If the electrode is free from paint or grease, and the earth is packed firmly, the Bureau of Standards has shown that contact resistance is negligible. Rust on an iron electrode has little or no effect; the iron oxide is readily soaked with water and has less resistance than most soils. But if an iron pipe has rusted through, the part below the break is not effective as a part of the earth electrode.

Resistance of Surrounding Earth: An electrode driven into earth of uniform resistivity radiates current in all directions. Think of the electrode as being surrounded by *shells of earth*, all of equal thickness (see Fig. 4).

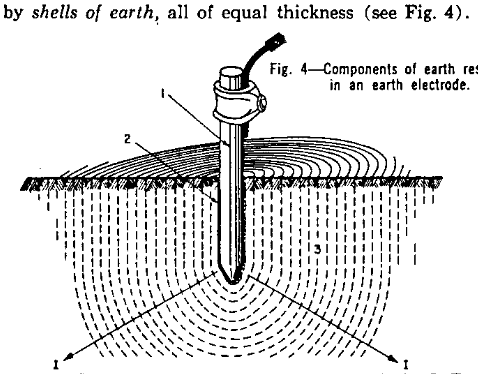


Fig. 4—Components of earth resistance in an earth electrode.

The earth shell nearest the electrode naturally has the smallest surface area and so offers the greatest resistance. The next earth shell is somewhat larger in area and offers less resistance. And so on out. Finally, a distance from the electrode will be reached where inclusion of additional earth shells does not add significantly to the resistance of the earth surrounding the electrode.

Generally, the resistance of the surrounding earth will be the largest of the three components making up the resistance of a ground connection. The several factors that can affect this value are discussed in Section II on Earth Resistivity. From Section II, you'll see that earth resistivity depends on the soil material, the moisture content, and the temperature. It is far from a constant, predictable value—ranging generally from 500 to 50,000 ohm-cm.*

PRINCIPLES INVOLVED IN EARTH-RESISTANCE TESTING

The resistance to earth of any system of electrodes *theoretically* can be calculated from formulas based upon the general resistance formula:

$$R = \rho \frac{L}{A}$$

where ρ is the resistivity of the earth in ohm-cm, L is the length of the conducting path, and A is the cross-sectional area of the path. Prof. H. B. Dwight of Massachusetts Institute of Technology developed rather complex formulas for the calculation of the resistance to earth for any distance from various systems of electrodes (Ref. 11). All such formulas can be simplified a little by basing them on the assumption that the earth's resistivity is uniform throughout the entire soil volume under consideration.

* An ohm-centimeter (abbreviated ohm-cm) is defined as the resistance of a cube of material (in this case, earth) with the cube sides being measured in centimeters.

Typical use of a Megger Null-Balance earth tester with digital read-out of measured earth resistance.

Because the formulas are complicated, and earth resistivity is neither uniform nor constant, a simple and direct method of measuring earth resistance is needed. This is where we come in with our Megger® earth tester — a self-contained portable instrument that is reliable and easy to use. With it, you can check the resistance of your earth electrode while it's being installed; and, by periodic tests, observe any changes with time.

To understand the principle of earth testing, consider the schematic diagram Fig. 5a. Bear in mind our previous observation with reference to the earth shell diagram Fig. 4: with increased distance from an electrode, the earth shells are of greater surface area and therefore of lower resistance. Now, assume that you have three rods driven into the earth some distance apart and a voltage applied, as shown in Fig. 5a. The current between rods 1 and 2 is measured by an ammeter; the potential difference (voltage) between rods 1 and 3 is measured by a voltmeter.

If rod 3 is located at various points between rods 1 and 2, preferably in a straight line*, you can get a series of voltage readings. By Ohm's Law ($R = E/I$) you can determine the earth resistance at any point measured. For example, if the measured voltage E between rods 1 and 3 is 30 volts and the measured current I is 2 amperes, the resistance of the earth R at that point would be 15 ohms.

The series of resistance values can be plotted against distance to obtain a curve (Fig. 5b). Note that as rod 3 is moved away from rod 1, the resistance values increase but the amount of increase gets less and less until a point is reached where the *rate of increase becomes so small that it can almost be considered constant* (20 ohms in Fig. 5b). The earth shells between the two rods (1 and 3) have so great a surface area that they add little to the total resistance. Beyond this point, as rod 3 approaches the earth shells of rod 2, resistance gradually picks up. Near rod 2, the values rise sharply.

Now, let's say that rod 1 is our earth electrode under test. From a typical earth-resistance curve, such as Fig. 5b, what is the resistance to earth of this rod? We call rod 2 *current-reference probe* C and rod 3, *potential-reference probe* P (simply for convenience in identification). *The correct resistance is usually obtained if P (rod 3) is placed at a distance from the center of the earth electrode (rod 1) about 62% of the distance between the earth electrode and C (rod 2).*

For example, in Fig. 5b the distance D from the earth electrode to C is 100 feet. Taking 62% of this distance, we get 62 feet. From Fig. 5b, the resistance for this distance is 20 ohms. This is the measured resistance of the earth electrode.

* Actually current can exist in other paths between the two fixed electrodes, so that rod 3 could (and might have to be) located at other than along a straight line.

This rule works well for simple electrodes, such as a driven rod. It also works for a small group of rods. But you must know the true electrical center of the electrode system fairly accurately. Also, accuracy of readings is better if the earth resistivity between the three electrodes is reasonably constant. Finally, C should be far enough away from the earth-electrode system so that the 62% distance is out of the "sphere of influence" of the earth-electrode. (See discussion with reference to Figs. 8 and 9).

Basically, you now have the principle of earth-resistance testing. The rest is refinement— in test methods, use of electrodes or electrode systems, and information about earth resistivity, as covered in later portions of this manual.

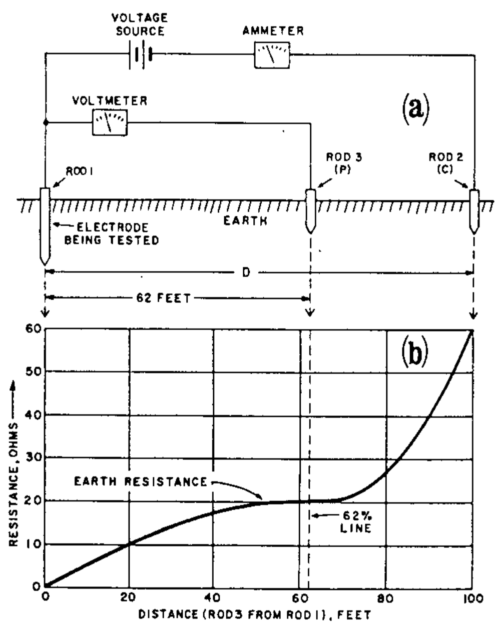


Fig. 5—Principle of an earth-resistance test.

BASIC TEST METHODS FOR EARTH RESISTANCE

Megger instruments for earth-resistance tests include: (1) a voltage source, (2) an ohmmeter to measure resistance directly, and (3) switches to change the instrument's resistance range. Extension wires connect terminals on the instrument to the earth and reference electrodes, as will be described. A hand-cranked generator or battery-powered oscillator supplies the required current; you read resistance in ohms from a pointer on a scale or a digital read-out.

There are two basic test methods, shown schematically in Figs. 6 and 7, namely:

1. Direct Method, or Two-Terminal Test.
2. Fall-of-Potential Method, or Three-Terminal Test.

Direct Method: When using a four-terminal instrument, P_1 and C_1 terminals connect to the earth electrode under test; P_2 and C_2 terminals connect to an all-

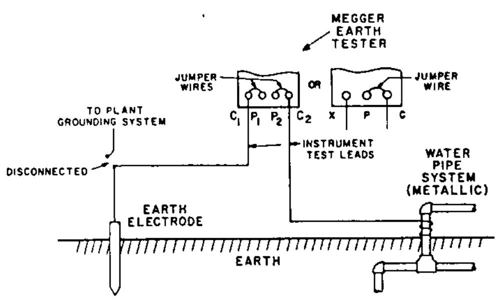


Fig. 6—"Direct Method" or "Two-Terminal" earth-resistance test.

metallic water-pipe system. With a three-terminal instrument, connect X to the earth electrode, P and C to the pipe system (Fig. 6). If the water system is extensive (covering a large area), its resistance should only be a fraction of an ohm. You can then take the instrument reading as being the resistance of the electrode under test.

The Direct Method is the simplest way to make an earth-resistance test. With this method, resistance of two electrodes in series is measured—the driven rod and the water system. But there are three important limitations:

1. The water-pipe system must be extensive enough to have a negligible resistance.
2. The water-pipe system must be *metallic* throughout, without any insulating couplings or flanges.
3. The earth electrode under test must be far enough away from the water-pipe system to be outside its sphere of influence.

In some locations, your earth electrode may be so close to the water-pipe system that you can not separate the two by the required distance for measurement by the two-terminal method. Under these circumstances, if conditions 1 and 2 above are met, you can connect to the water-pipe system and obtain a suitable earth electrode. As a precaution against any possible future changes in the resistance of the water-pipe system, however, you should also install an earth electrode.

Fall-of-Potential Method: This three-terminal test is the method described previously with reference to Fig. 5. With a four-terminal tester, P_1 and C_1 terminals on the instrument are jumpered and connected to the earth electrode under test. With a three-terminal instrument, connect X to the earth electrode. The driven reference rod C should be placed as far from the earth electrode as practical; this distance may be limited by the length of extension wire available, or the geography of the surroundings (see Fig. 7).

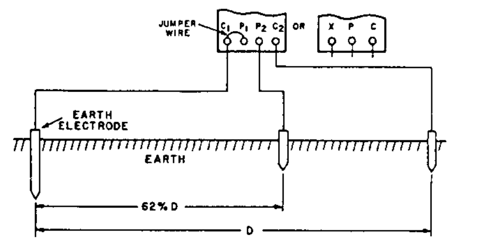


Fig. 7—"Fall-of-Potential" or "Three-Terminal" earth-resistance test.

Potential-reference rod P is then driven in at a number of points roughly on a straight line between the earth electrode and C. Resistance readings are logged for each of the points. A curve of resistance vs distance, like Fig. 5b, is then drawn. Correct earth resistance is read from the curve for the distance that is about 62% of the total distance from the earth electrode to C. In other words, if the total distance is D, the 62% distance is 0.62D; for example, if D is 120 feet, the distance value for earth resistance is 0.62 x 120 or 74 feet.

EFFECTS OF DIFFERENT REFERENCE PROBE LOCATIONS

Now, you may ask: if the right location for probe P is always 62% of the distance between the earth electrode and C, why bother with all the tests at other locations for P? Why not just drive P in at the 62% distance and assume that the measured resistance is the correct earth resistance? The following paragraphs should help answer these questions.

Minimum Distance for C: Consider Fig. 8 which shows earth shells around the earth electrode and reference probe C. In Fig. 8a, C is so close to the earth electrode that the earth shells seriously overlap. Then you don't get the leveling off of measured resistance as P is moved away from the earth electrode; the shells of C *add to* the shells of the earth electrode, so the resistance keeps increasing.

In Fig. 8b, C is placed farther away. Then the measured resistance levels off enough and at the 62% distance it is very close to the actual earth resistance. The reason for having C farther away is to get assurance that the 62% value is "in line" with other values on the curve. The value could only be wrong (assuming there are no measuring mistakes) if the soil conditions at the 62% point vary from conditions at other points, causing changes in earth resistivity. You want to get some degree of flatness or leveling off of your curve to make such a variation easily noticeable.

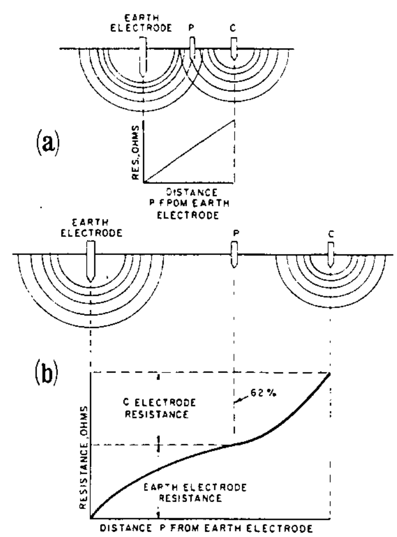


Fig. 8—Effect of C location on the earth-resistance curve.

Measuring the resistance of a ground system on a pad-mounted transformer at a manufacturing plant.

As a practical example of this effect, consider the case illustrated in Fig. 9. This shows two earth-resistance curves for two locations of C. Curve A was obtained when C was 100 feet from the earth electrode; Curve B when C was 700 feet away. Curve A shows that C was too close to the earth electrode; Curve B shows the desired tendency toward leveling out of the measured resistance. The 62% distance gives resistance values nearly the same in this case since the earth resistivity is fairly uniform.

Simplified Fall-of-Potential Test: The preferred test method is to always gather sufficient data to plot the actual curve of resistance versus distance. In the event that this is impossible, a simplified test might be used with a compromise on accuracy. This procedure is similar to that outlined under Fall-of-Potential Method, but you start with P mid-way between the earth electrode and C.

This reading with P at 50% of the distance from the earth electrode to C is noted as R_1. Reference probe P is then moved to a location 40% of the distance to C. The reading at this point is noted as R_2. A third reading, R_3, is made with P at a 60% distance. The average of R_1, R_2, and R_3 is calculated as R_A. Subtract R_A from R_3 and express the result as a percentage of R_A. If 1.2 times this percentage is less than your desired test accuracy, R_A can be used as the test result. As an example of this technique, use the data from curve B in Fig. 9 as follows:

$$R_1 = 55\Omega \qquad R_2 = 58\Omega \qquad R_3 = 59\Omega$$

$$R_A = \frac{55 + 58 + 59}{3} = 57.3\Omega$$

$$\frac{R_3 - R_A}{R_3} = \frac{59 - 57.3}{59} = 2.8\%$$

$$2.8\% \times 1.2 = 3.4\%$$

If your desired accuracy was 5%, 57Ω (R_A) could be used as the result. If the result is not within the required accuracy, probe C has to be placed farther away and the tests repeated. This method can give sufficient accuracy but will always give values on the low side. (See discussion following with reference to Table I.)

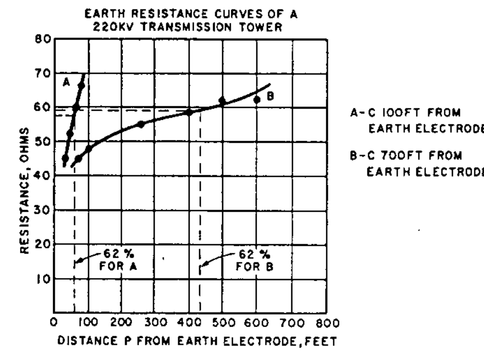


Fig. 9—Example of how C location affects the earth-resistance curve.

Some Rules of Thumb on Spacing P and C: For testing a single earth electrode, C can usually be placed 50 feet from the electrode under test, with P placed about 31 feet away. With a small grid of two earth electrodes, C can usually be placed about 100 to 125 feet from the electrode under test; P correspondingly can

TABLE I—Guide to Approximate Location of Reference Probes (See Note 1)

MAXIMUM DIMENSION, FT. (See Note 2)	DISTANCE TO P, FT.	DISTANCE TO C, FT.
2	40	70
4	60	100
6	80	125
8	90	140
10	100	160
12	105	170
14	120	190
16	125	200
18	130	210
20	140	220
40	200	320
60	240	390
80	280	450
100	310	500
120	340	550
140	365	590
160	400	640
180	420	680
200	440	710

Note 1—Based upon data in Reference 2.
Note 2—For example, the diagonal across an area surrounded by an earthed fence.

be placed about 62 to 78 feet away. If the earth electrode system is large—consisting, for example, of several rods or plates in parallel—the distance for C must be increased to possibly 200 feet, and for P to some 125 feet. You'll need even greater distance for complex electrode systems that consist of, say, a large number of rods or plates and other metallic structures —all bonded together. For an earth electrode system covering a large area, refer to Appendix II and III for additional techniques.

Table I is a useful guide to reference probe location. You find the "Maximum Dimension" figure by taking the diagonal distance across your electrode system area. For example, if the area measures 100 by 100 feet, the diagonal equals about 140 feet. From the table, you run down the first column to 140 and read across that P should be 365 feet from the electrode and C, 590 feet.

HOW TO IMPROVE EARTH RESISTANCE

When you find that your earth-electrode resistance is not low enough, there are several ways you can improve it:

1. Lengthen the earth electrode in the earth

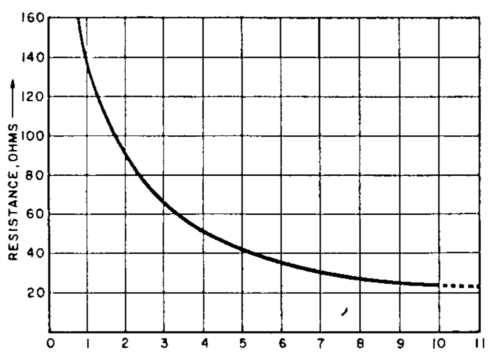


Fig. 10—Earth resistance decreases with depth of electrode in earth. (Source: Reference 19)

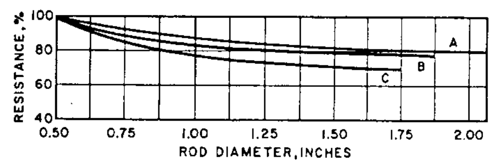


Fig. 11—Diameter of a rod has little effect on its earth resistance.

Curve A, from Reference 19.

Curve B, average of Underwriters Laboratories tests at Chicago.

Curve C, average of Underwriters Laboratories tests at Pittsburgh.

2. Use multiple rods
3. Treat the soil.

Effect of Rod Size: As you might suspect, driving a longer rod deeper into the earth, materially decreases its resistance. In general, *doubling the rod length reduces resistance by about 40%.* The curve of Fig. 10 shows this effect. For example, note that a rod driven two feet down has a resistance of 88 ohms; the same rod driven 4 feet down has a resistance of about 50 ohms. Using the 40% reduction rule, 88 × 0.4 = 35 ohms *reduction.* A 4-foot deep rod, by this calculation would have a resistance of 88−35 or 53 ohms—comparing closely with the curve values.

You might also think that increasing the electrode diameter would lower the resistance. It does, but only a little. For the same depth, doubling the rod's diameter reduces the resistance only about 10%. Fig. 11 shows this relationship. For example, a 10-foot deep rod, ⅝ inch in diameter, has a resistance of 6.33 ohms; increasing its diameter to 1¼ inch lowers the resistance only to 5.6 ohms. For this reason, you normally only consider increasing the rod diameter if you have to drive it into hard terrain.

Use of Multiple Rods: Two well-spaced rods driven into the earth provide parallel paths. They are, in effect, two resistances in parallel. The rule for two resistances in parallel does not apply exactly; that is, the result-

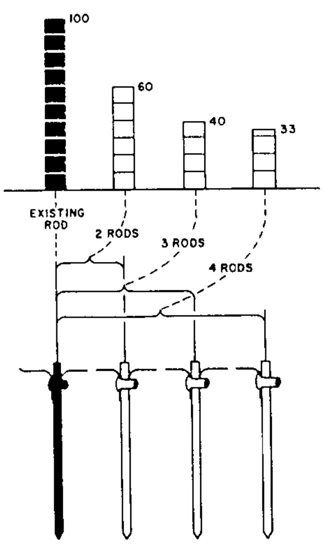


Fig. 12—Average results obtained from multiple-rod earth electrodes.*

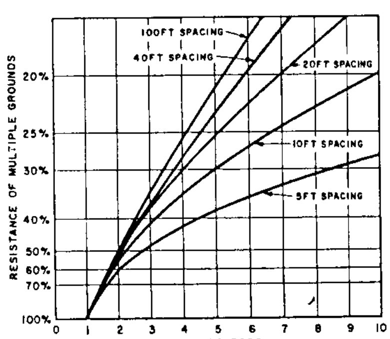


Fig. 13—Comparative resistance of multiple-rod earth electrodes. Single rod equals 100%.*

* Source: Reference 20

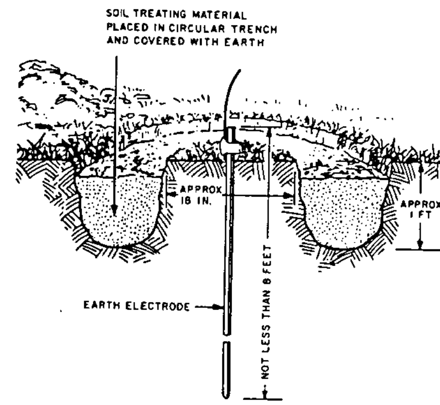


Fig. 14—Trench method of soil treatment.*

ant resistance is not one-half the individual rod resistances (assuming they are of the same size and depth). Actually, the reduction for two equal-resistance rods is about 60%. If three rods are used, the reduction is 40%, and if four, 33% (see Fig. 12).

When you use multiple rods, they must be spaced apart further than the length of their immersion. There are theoretical reasons for this, but you need only refer to curves such as Fig. 13. For example, if you have two rods in parallel and 10-foot spacing, resistance is lowered about 60%. If the spacing is increased to 20 feet, reduction is about 50%.

Treatment of the Soil: Chemical treatment of soil is a good way to improve earth-electrode resistance when you can't drive deeper ground rods—because of hard underlying rock, for example. It is beyond the scope of this manual to recommend the best treatment chemicals for all situations. You have to consider the possible corrosive effect on the electrode. Magnesium sulfate, copper sulfate, and ordinary rock salt are

* Source: Reference 20

suitable non-corrosive materials. Magnesium sulfate is the least corrosive, but rock salt is cheaper and does the job if applied in a trench dug around the electrode. (Fig. 14).

Chemical treatment is not a permanent way to improve your earth-electrode resistance. The chemicals are gradually washed away by rainfall and natural drainage through the soil. Depending upon the porosity of the soil and the amount of rainfall, the period for replacement varies. It may be several years before another treatment is required.

Chemical treatment also has the advantage of reducing the seasonal variation in resistance that results from periodical wetting and drying out of the soil. (See curves of Fig. 15). However, you should only consider this method when deep or multiple electrodes are not practical.

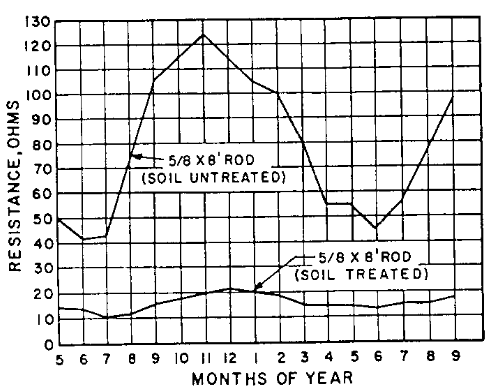


Fig. 15—Chemical treatment of soil lessens seasonal variation of electrode's earth-resistance.*

See APPENDIX I which describes the use of a nomograph relating length of rod, diameter of rod, and earth resistivity to earth resistance.

* Source: Reference 20

SECTION II

Earth Resistivity

As we've seen in Section I, the term, "earth resistivity", expressed in *ohm-centimeters* (abbreviated ohm-cm), is one basic variable affecting resistance to earth of an electrode system. But you found that the actual value of earth resistivity need not be measured to check the electrode earth resistance. Now we'll consider other fields where the value of resistivity is measured; also some of the factors affecting it that are of interest in earth testing.

Earth resistivity measurements can be used conveniently for geophysical prospecting— to locate ore bodies, clays, and water bearing gravel beneath the earth's surface. The measurement can also be used to determine depth to bed rock and thickness of glacial drift.

Measurements of earth resistivity are useful also for finding the best location and depth for low-resistance electrodes. Such studies are made, for example, when a new electrical unit is to be constructed— a generating station, sub-station, transmission tower, or telephone central office.

Finally, earth resistivity may be used to indicate the degree of corrosion to be expected in underground pipelines for water, oil, gas, gasoline, etc. In general, spots where the resistivity values are low tend to increase corrosion. This same kind of information is a good guide for installing cathodic protection.

HOW EARTH RESISTIVITY IS MEASURED

A four-terminal instrument is used to measure earth resistivity. Now, however, you use *four* small-sized electrodes *driven down the same amount and equal distances apart* in a straight line (Fig. 16). Four separate lead wires connect the electrodes to the four terminals on the instrument, as shown. Hence the name of this test: *the four-terminal method.*

Dr. Frank Wenner of the U. S. Bureau of Standards developed the theory behind this test in 1915 (see reference 10). He showed that, if the electrode depth *(B)* is kept small compared to the distance between the electrodes *(A)**, the following formula applies:

$$\rho = 2\pi AR$$

where ρ is the average soil resistivity to depth A in ohm-cm, π is the constant 3.1416, A is distance between the electrodes in cm, and R is the Megger instrument reading in ohms.

In other words, if the distance A between electrodes is 4 feet, you obtain the average earth resistivity to a depth of 4 feet as follows:

1. Convert the 4 feet to centimeters to obtain A in the formula:
   $4 \times 12 \times 2.54$ cm $= 122$ cm
2. Multiply $2\pi A$ to obtain a constant for a given test set-up:
   $2 \times 3.14 \times 122 = 766$

Now, for example, if your instrument reading is 60 ohms, the earth resistivity would be 60×766, or 45,960 ohm-cm.

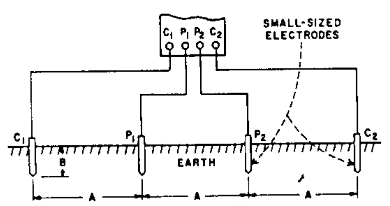


Fig. 16—"Four-Terminal" method of measuring earth resistivity.

* B = 1/20A is generally recommended.

PRACTICAL EXAMPLE OF TEST METHOD*

A petroleum company had a 10-inch pipeline 6300 feet long running through rugged terrain. After a corrosion leak, they wanted to check out earth resistivity along the line. Low-resistance spots would most likely require attention. So they used a Megger instrument to make a survey along the line.

First, average depth of the pipeline was found from a profile map. It was four feet, so the four electrodes were tied together 4 feet apart with strong cotton cord. They decided to check soil resistivity every 20 feet along the line. Fig. 17 shows a portion of the results; pit depth of corrosion and Megger instrument readings are both plotted for points along the pipeline. Note that for low resistance readings, more corrosion was found.

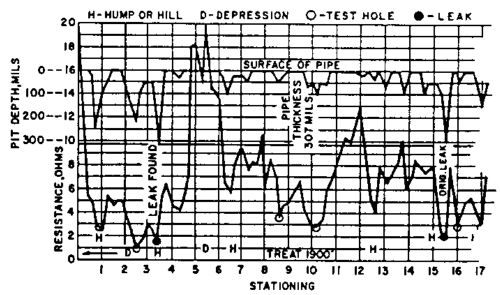


Fig. 17—Earth-resistivity survey of pipeline shows where corrosion is most likely to occur. (Source: Reference 18)

* Reference 18

TYPE OF SOIL AFFECTS RESISTIVITY

Whether a soil is largely clay or very sandy, for example, can change the earth resistivity very much. It isn't easy to define exactly a given soil; "clay" can cover a wide variety of soils. So we can't say that any given soil has a resistivity of so many ohm-cm. Accompanying Tables II and III from two different reference books show the wide range in values. Note also the spread of values for the same general types of soil. See also Fig. 18 on page 33.

TABLE II—Resistivities of Different Soils*

SOIL	RESISTIVITY OHM-CM AVERAGE	MIN.	MAX.
Fills—ashes, cinders, brine wastes	2,370	590	7,000
Clay, shale, gumbo, loam	4,060	340	16,300
Same—with varying proportions of sand and gravel	15,800	1,020	135,000
Gravel, sand, stones, with little clay or loam	94,000	59,000	458,000

* U. S. Bureau of Standards Technical Report 108

TABLE III—Resistivities of Different Soils**

SOIL	RESISTIVITY, OHM-CM (RANGE)
Surface soils, loam, etc.	100 — 5,000
Clay	200 — 10,000
Sand and gravel	5,000 — 100,000
Surface limestone	10,000 — 1,000,000
Limestones	500 — 400,000
Shales	500 — 10,000
Sandstone	2,000 — 200,000
Granites, basalts, etc.	100,000
Decomposed gneisses	5,000 — 50,000
Slates, etc.	1,000 — 10,000

** Evershed & Vignoles Bulletin 245.

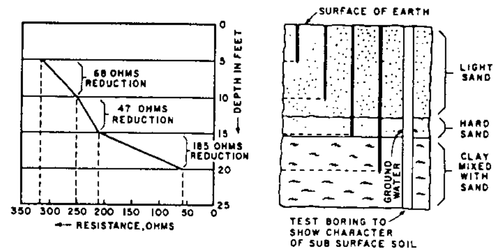


Fig. 18—Deeper earth electrodes lower the resistance. These graphs show the relation between character of soil and resistance of driven electrode at increased depths.

RESISTIVITY DECREASES WITH MOISTURE AND DISSOLVED SALTS

In soil, conduction of current is largely electrolytic. So the amount of moisture and salt content of soil radically affect its resistivity. Amount of water in soil varies, of course, with the weather, time of year, nature of sub-soil, and depth of the permanent water table. The accompanying Table IV shows typical effects of water in soil; note that when dry the two types of soil are good insulators (resistivities greater than 1000×10^6 ohm-cm). With a moisture content of 15%, however, note the drastic decrease in resistivity (by a factor of about 100,000).

TABLE IV—Effect of Moisture Content on Earth Resistivity †

MOISTURE CONTENT, % BY WEIGHT	RESISTIVITY, OHM-CM TOP SOIL	SANDY LOAM
0	$1,000 \times 10^6$	$1,000 \times 10^6$
2.5	250,000	150,000
5	165,000	43,000
10	53,000	22,000
15	21,000	13,000
20	12,000	10,000
30	10,000	8,000

† From "An Investigation of Earthing Resistance", by P. J. Higgs, I.E.E. Jour., vol. 68, p. 736, February 1930.

Actually, pure water has an infinitely high resistivity. Naturally-occurring salts in the earth, dissolved in water, lower the resistivity. Only a small amount of a salt* can reduce earth resistivity quite a bit (see Table V). As we noted in Section I, this effect can be useful to provide a good low-resistance electrode, in place of an expensive, elaborate electrode system.

TABLE V—Effect of Salt Content on Earth Resistivity**

ADDED SALT % BY WEIGHT OF MOISTURE	RESISTIVITY, OHM-CM
0	10,700
0.1	1,800
1.0	460
5	190
10	130
20	100

** For sandy loam—moisture content, 15% by weight; temperature, 17°C (63°F).

EFFECT OF TEMPERATURE ON EARTH RESISTIVITY

Not much information has been collected on the effects of temperature. Two facts lead to the logical conclusion that an increase in temperature will decrease resistivity: (1) water present in soil mostly determines the resistivity, and (2) an increase in temperature markedly decreases the resistivity of water. The results shown in Table VI confirm this. Note that when water in the soil freezes, the resistivity jumps appreciably; ice has a high resistivity. Note also that the resistivity continues to increase as temperatures go below freezing. You could have a really-high value at the North Pole!

TABLE VI—Effect of Temperature on Earth Resistivity†

TEMPERATURE C	F	RESISTIVITY, 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

† For sandy loam, 15.2% moisture.

* By "salt" we mean not just the kind you use to season food (sodium chloride) though this kind can occur in the soil. Other kinds include copper sulphate, sodium carbonate, and others (see "Treatment of Soil", Section I, P. 27)

From the table, note that a 54-degree drop in temperature (from 68°F to 14°F) causes almost a 50-fold increase in resistivity.

SEASONAL VARIATIONS IN EARTH RESISTIVITY

We have seen the effects of temperature, moisture, and salt content upon earth resistivity. It makes sense, therefore, that the resistivity of soil will vary considerably at different times of the year. This is particularly true in locations where there are more extremes of temperature, rainfall, dry spells, and other seasonal variations.

From all the preceding discussion, you can see that earth resistivity is a very variable quantity. If you want to know what the value is at a given location, at a given time of the year, the only safe way is to measure it. When you use this value for survey work, the *change* in the value, caused by changes in the nature of the sub-soil, is the important thing; from the variations in resistivity you can obtain useful survey results.

As covered in Section I, the other main reason for being interested in earth resistivity is to design earth-electrode systems for electrical power systems, lightning arresters, and so on. Earth resistance varies directly with earth resistivity and it's helpful to know what factors affect resistivity.

The curves of Fig. 19 illustrate several worthwhile points. They show the expected change in earth resistance (due to resistivity changes) over a 1½-year period; they also show that the deeper electrode gives a more stable and lower value. We conclude that the moisture content and temperature of the soil become more stable at greater distances below the earth's surface. Therefore, the earth electrode, should reach a deep enough level to provide:

1. Permanent moisture content (relatively speaking)
2. Constant temperature (below frost line; again relatively speaking).

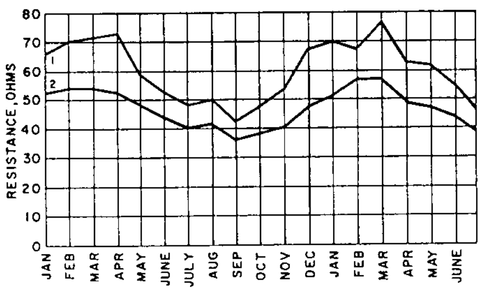


Fig 19—Seasonal variation of earth resistance with an electrode of ¾-inch pipe in rather stony clay soil. Depth of electrode in earth is 3 ft for Curve 1, and 10 ft for Curve 2. (Source: Reference 9)

DETERMINING A GOOD ELECTRODE LOCATION

A good, low-resistance earth electrode depends upon a low-resistivity soil in a spot where you can drive in your electrodes. There are two approaches to picking your location:

1. Drive rods in various locations to such depths as may be required and test their resistances while they are being driven.
2. Measure the earth resistivity *before* driving ground rods. Then calculate the number and length of rods required.

To get a low-resistance electrode in an unfavorable location, lay out straight lines 10 feet apart, covering the area. Drive four stakes 10 feet apart, but not more than six inches deep, along a line a-b-c-d, as shown in Fig. 20. Measure the resistance R between stakes b and c, using the method described for earth resistivity.

Then, shift the stakes along the line in question to points b-c-d-e, c-d-e-f, and so on (see Fig. 20) and test until the entire line has been covered. Next, move to the next line and repeat the process until the whole chosen area has been covered. The location giving the lowest value for R has the lowest specific resistance for the soil to the chosen depth of 10 feet. The spot is likely to give you the best earth electrode.

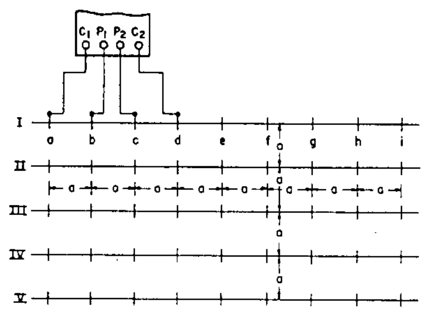
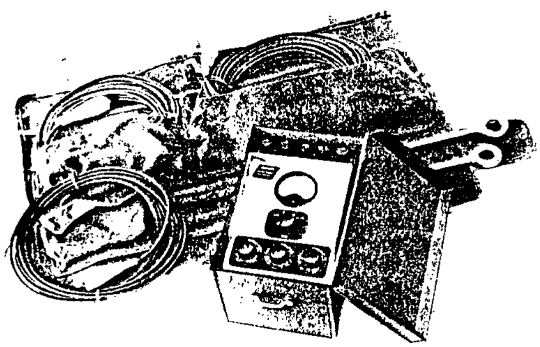


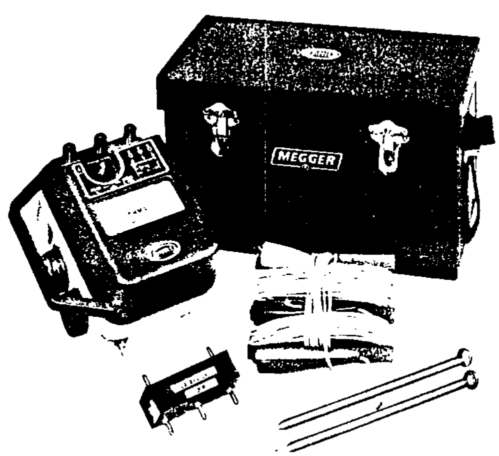
Fig. 20—Method of prospecting for best earth electrode location to a depth a. Location giving lowest reading on the Megger earth tester is the most desirable.

If you want results affected by the average earth resistivity to a depth of 20 feet, repeat the survey on lines 20 feet apart and with stakes spaced 20 feet apart. Such surveys do not require much time and can pay off in assuring a good grounding system.

Alternate Method: Another way is to drive rods or pipes in various locations to such depths as may prove practicable, testing their resistance *while they are being driven.* In this manner, you can usually tell at once when moisture or other good conducting earth is reached. However, the work involved is apt to be much more than with the first method.



Typical earth-resistance test kit with ground rods and cable, plus a Megger Null-Balance instrument in carrying case.



The Direct-Reading Megger Earth Tester, with vinyl carrying case, and compact lightweight Accessory kit items.

Appendix I Nomograph Guide to Getting Acceptable Earth Resistance*

Dr. L. E. Whitehead of the DuPage Laboratories developed a nomograph (Fig. 21) which can be a helpful guide in meeting the established standard for a minimum earth resistance. If you have a given earth-electrode system and find that your Megger instrument reading is too high, the graph can be used to show what you must do to lower the value. Note that it covers three variable conditions that affect earth resistance of the electrode: *earth resistivity, length of rod, and diameter of rod.*

To illustrate use of the nomograph, let's take an example. Assume you have a ⅝-inch rod driven 10 feet into the soil. Your Megger instrument indicates an earth resistance of 6.6 ohms. But let's say your specification for this resistance is "no more than 4 ohms." To get this, you can change one or more of the three variables; the simplest and most effective being depth of the driven rod. To find the required depth to give you a 4-ohm earth resistance, proceed as follows: With a ruler, draw a line from the 10-foot point in the L line to the ⅝-inch point in the d line; this gives a reference point where the line crosses the q line. Connect this reference point with 6.6 ohms—the measured resistance on the R line, as shown in Fig. 21, read the value of earth resistivity where this line crosses the ρ line. The value is 2000 ohm-cm.

To determine the required rod depth for a 4-ohm earth resistance, draw a line from this point on the R line through the 2000 point on the line until you cross the q line. The dashed line on Fig. 21 shows this step. Now, assuming you keep rod diameter unchanged, connect the ⅝ point on d line through your new reference point on q and extend the line to L. This gives you the required rod depth for the 4-ohm resistance value. Finally, take a new instrument reading to check the value, because earth resistivity may not be constant (as the nomograph assumes).

Another way to reduce the earth resistance would be to lower the earth resistivity. Note in Fig. 21 that if you draw a line from a reference point 1 (leaving rod depth and diameter unchanged), you would need

* Source: Reference 21

to reduce earth resistivity to about 1000 ohm-cm to give the required 4-ohm earth resistance. You could do this by chemical treatment, as described earlier, but normally the deeper rod is the easier way.

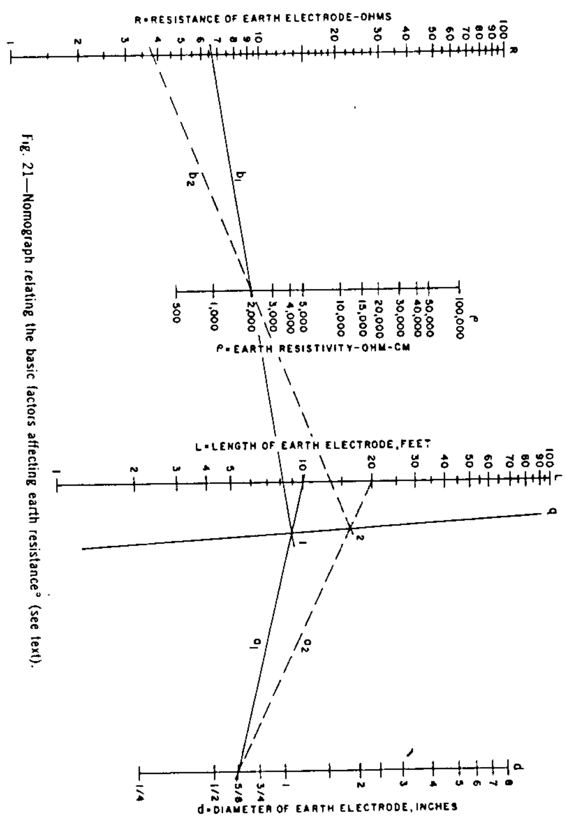


Fig. 21—Nomograph relating the basic factors affecting earth resistance° (see text).

Appendix II Measurement of the Resistance of Large Earth-Electrode Systems: Intersecting Curves Method*

The difficulties of measuring the resistance of large electrode systems involve the use of very long leads to connect the potential and current probes. An alternative method, in which such long leads are not necessary, has been devised. The basic principle is to obtain earth-resistance curves for several current-electrode spacings, and, by assuming a number of successive positions for the electrical center of the system, to produce intersection curves which will give the earth resistance and the position of the electrical center.

Some rather difficult problems are encountered when the resistance of an earth-electrode system, consisting of a number of rods, tapes, etc., all connected in parallel and spread over a large area, is to be measured. The usual method of measurement that worked very well has one disadvantage: namely, that it is generally necessary to place the auxiliary current probe at a considerable distance from the earth-electrode system. In some cases this distance can be as much as 3000 ft, and this is not always convenient or possible.

A method which does not require such long lengths of cable would obviously be better, therefore, the following is suggested.

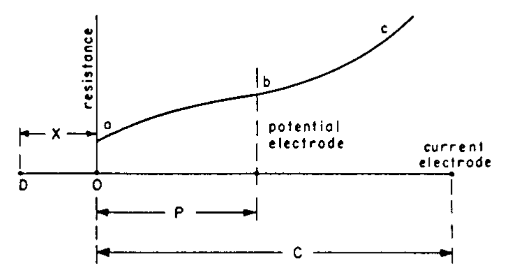


Fig. 22—Earth-resistance curve applicable to systems of a large area.

* Source: Reference 22

Suppose that all measurements, are made from an arbitrary starting point O, the distance C to the current probe and the variable distance P to the potential probe being measured from this point. Then a curve such as abc (Fig. 22), giving the measured resistance against the value of P, can be obtained. Now suppose the electrical center of the earth-electrode system is actually at D, distance X from O. Then the true distance from the center to the current probe is C + X, and the true resistance is obtained when the potential probe is at a distance 0.618 (C + X) from D. This means that the value of P, measured from O, is 0.618 (C + X) − X. If X is now given a number of values, the corresponding values of P can be calculated and the resistance read off the curve. These resistances can be plotted against the values of X in another curve. When this process is repeated for a different value of C, and another curve of resistance against X obtained, the two curves should cross at the required resistance. The process can be repeated for a third value of C as a check. These curves are called intersection curves. It has been assumed that D, O and C are in the same straight line.

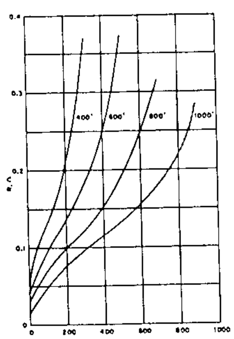


Fig. 23—Earth-resistance curves for a substation.

TEST AT A LARGE SUBSTATION

Tests were made at a station which covers an area approximately 300 ft x 250 ft. The earthing system consists of a number of earth plates and rods joined together by copper cables. The testing line was run out from a point on the face approximately halfway along one side, and the current electrode was placed at distances of 400, 600, 800 and 1000 ft. from the starting point. The resulting earth-resistance curves are given in Fig. 23. The intersection curves are plotted and the final value of resistance is found in Fig. 24.

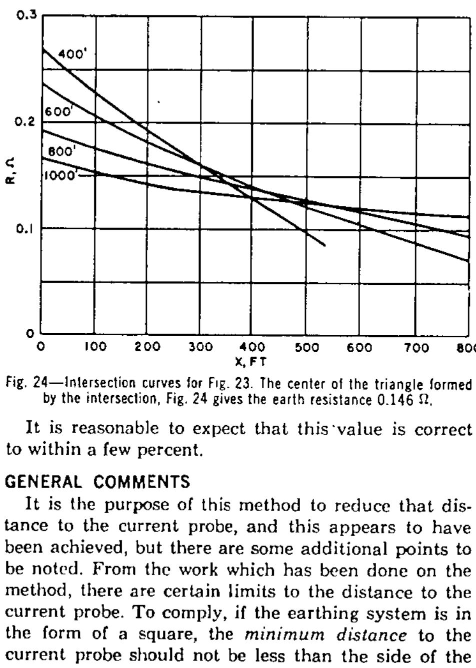


Fig. 24—Intersection curves for Fig. 23. The center of the triangle formed by the intersection, Fig. 24 gives the earth resistance 0.146 Ω.

It is reasonable to expect that this value is correct to within a few percent.

GENERAL COMMENTS

It is the purpose of this method to reduce that distance to the current probe, and this appears to have been achieved, but there are some additional points to be noted. From the work which has been done on the method, there are certain limits to the distance to the current probe. To comply, if the earthing system is in the form of a square, the *minimum distance* to the current probe should not be less than the side of the square. On the other hand, the *maximum* distance should not be too great, if it is, the resulting curve is very flat, and the intersection point becomes rather indefinite. Again, for a square system, this maximum distance should not exceed twice the side of the square. For other shapes of earth-electrode systems, it is necessary to judge suitable minimum and maximum values for the distance to the current probe.

Appendix III Measurement of the Resistance of Large* Earth Electrode Systems: Slope Method.

It has been shown that the true earth resistance of an electrode system is obtained when the temporary potential probe P is positioned at a distance from the electrical center of the system equal to 61.8% of the distance from the electrical center to the temporary current probe.

This principle is used in the technique called "Intersecting Curves" explained in APPENDIX I. It becomes apparent that the method is complex in nature and requires some "trial and error" calculations.

A further technique was evolved and is described here. It is easier to use and has been shown to give satisfactory results, both in theoretical and practical cases, and when the soil is non-homogeneous. It is called the Slope Method.

For the purpose of applying this technique in practice, the following is a simplified step-by-step procedure.

1. Choose a convenient rod E to which the Earth Tester can be connected. E is one of many paralleled rods forming the complex earth system.

Fig. 25: Potential probe locations for using the Slope Method.

2. Insert the current probe at a distance C from E (Distance C is normally 2 to 3 times the maximum dimension of the system).
3. Insert potential probes at distances equal to 0.2C, 0.4C and 0.6C.
4. Measure the earth resistance using each potential probe in turn. Let these resistance values be R_1, R_2 and R_3 respectively.
5. Calculate the value of $\dfrac{R_3 - R_2}{R_2 - R_1}$

   This is called μ and represents the change of slope of the Resistance/Distance curve.
6. Refer to the table below and find the corresponding value of P_T/C for μ.
7. Since C is already known, calculate P_T and insert a potential probe at this distance from E.
8. Measure the earth resistance which should be the true resistance.
9. Repeat the whole process for a larger value of C. If the "true" resistance decreases appreciably as C is increased, it is necessary to increase C still further.

NOTE: As with other earth testing techniques, some experimentation may be necessary to ascertain if the practical result is as accurate as the theory appears to indicate.

One particular observation on the Slope Method is that if the calculation of μ is greater than that given in the table, the distance C must be increased.

TABLE VII—Values of P_T/C for Various Values of μ.

μ	P_T/C	μ	P_T/C	μ	P_T/C
0.40	0.643	0.80	0.580	1.20	0.494
0.41	0.642	0.81	0.579	1.21	0.491
0.42	0.640	0.82	0.577	1.22	0.488
0.43	0.639	0.83	0.575	1.23	0.486
0.44	0.637	0.84	0.573	1.24	0.483
0.45	0.636	0.85	0.571	1.25	0.480
0.46	0.635	0.86	0.569	1.26	0.477
0.47	0.633	0.87	0.567	1.27	0.474
0.48	0.632	0.88	0.566	1.28	0.471
0.49	0.630	0.89	0.564	1.29	0.468
0.50	0.629	0.90	0.562	1.30	0.465
0.51	0.627	0.91	0.560	1.31	0.462
0.52	0.626	0.92	0.558	1.32	0.458
0.53	0.624	0.93	0.556	1.33	0.455
0.54	0.623	0.94	0.554	1.34	0.452
0.55	0.621	0.95	0.552	1.35	0.448
0.56	0.620	0.96	0.550	1.36	0.445
0.57	0.618	0.97	0.548	1.37	0.441
0.58	0.617	0.98	0.546	1.38	0.438
0.59	0.615	0.99	0.544	1.39	0.434
0.60	0.614	1.00	0.542	1.40	0.431
0.61	0.612	1.01	0.539	1.41	0.427
0.62	0.610	1.02	0.537	1.42	0.423
0.63	0.609	1.03	0.535	1.43	0.418
0.64	0.607	1.04	0.533	1.44	0.414
0.65	0.606	1.05	0.531	1.45	0.410
0.66	0.604	1.06	0.528	1.46	0.406
0.67	0.602	1.07	0.526	1.47	0.401
0.68	0.601	1.08	0.524	1.48	0.397
0.69	0.599	1.09	0.522	1.49	0.393
0.70	0.597	1.10	0.519	1.50	0.389
0.71	0.596	1.11	0.517	1.51	0.384
0.72	0.594	1.12	0.514	1.52	0.379
0.73	0.592	1.13	0.512	1.53	0.374
0.74	0.591	1.14	0.509	1.54	0.369
0.75	0.589	1.15	0.507	1.55	0.364
0.76	0.587	1.16	0.504	1.56	0.358
0.77	0.585	1.17	0.502	1.57	0.352
0.78	0.584	1.18	0.499	1.58	0.347
0.79	0.582	1.19	0.497	1.59	0.341

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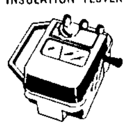

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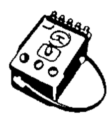

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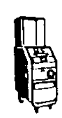

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