SOIL RESISTIVITY MEASUREMENTS

Soil resistivity directly affects the design of a grounding (earthing) electrode system and is the prime factor that determines the resistance to earth of a grounding electrode or grounding electrode system. Therefore, prior to the design and installation of a new grounding electrode system, the proposed location shall be tested to determine the soil's resistivity.

(See BS 7430:1998, IEEE STD 81, and MIL-HDBK-419A for more information.)

The terms “grounding” and “earthing” are used synonymously throughout this appendix.

B.1 SOIL RESISTIVITY VARIABILITY AND FACTORS AFFECTING SOIL RESISTIVITY

Soil resistivity varies widely by region due to differences in soil type and changes seasonally due to variations in the soil's electrolyte content and temperature. Therefore, it is recommended that these variations be considered when assessing soil resistivity. To help ensure expected grounding (earthing) electrode system resistance values are achieved throughout the year, worst-case soil resistivity values should be considered when designing a grounding electrode system.

Table B-1 lists ranges of soil resistivity for various types of soil. The values in Table B-1 are the expected values that should be seen when measuring soil resistivity.

**NOTE:** An ohm-centimeter (Ω·cm) is the resistance in ohms (Ω) of a one inch cube of soil, measured from opposite sides of the cube.

**TABLE B-1  SOIL RESISTIVITY FOR VARIOUS SOIL TYPES**

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashes, brine, or cinders</td>
<td>590</td>
<td>2,370</td>
<td>7,000</td>
</tr>
<tr>
<td>Concrete (below ground)</td>
<td></td>
<td>3,000</td>
<td></td>
</tr>
<tr>
<td>Clay, gumbo, loam, or shale</td>
<td>340</td>
<td>4,060</td>
<td>16,300</td>
</tr>
<tr>
<td>Clay, gumbo, loam, or shale with varying portions of sand and gravel</td>
<td>1,020</td>
<td>15,800</td>
<td>135,000</td>
</tr>
<tr>
<td>Gravel, sand, or stone with little clay or loam</td>
<td>59,000</td>
<td>94,000</td>
<td>458,000</td>
</tr>
</tbody>
</table>
NOTE: “Gumbo” is soil composed of fine-grain clays. When wet, the soil is highly plastic, very sticky, and has a soupy appearance. When dried, it develops large shrinkage cracks.

The resistivity of soil is primarily determined by the soil's electrolyte contents. Electrolytes consist of moisture, minerals, and dissolved salts. In general, soil resistivity decreases (improves) as electrolytes increase. Figure B-1 shows soil resistivity changes as a function of soil moisture content. The resistivity of the soil decreases rapidly as the moisture content increases from very little moisture to approximately 20 percent moisture.

<table>
<thead>
<tr>
<th>Moisture Content (% by weight)</th>
<th>Resistivity (Ω-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Top Soil Sandy Loam</td>
</tr>
<tr>
<td>&gt; 10⁹</td>
<td>&gt; 10⁹</td>
</tr>
<tr>
<td>2.5</td>
<td>250,000</td>
</tr>
<tr>
<td>5</td>
<td>165,000</td>
</tr>
<tr>
<td>10</td>
<td>53,000</td>
</tr>
<tr>
<td>15</td>
<td>19,000</td>
</tr>
<tr>
<td>20</td>
<td>12,000</td>
</tr>
<tr>
<td>30</td>
<td>6,400</td>
</tr>
</tbody>
</table>

Source: Soares Book on Grounding and Bonding, 9th addition (ISBN 1890659-36-3).

**FIGURE B-1** SOIL RESISTIVITY CHANGES AS A FUNCTION OF SOIL MOISTURE

The resistivity of soil is also affected by its temperature. In general, soil resistivity increases as temperature decreases. Figure B-2 shows soil resistivity changes as a function of soil temperature. As shown in the figure, the greatest rate of change in soil resistivity is at the point where moisture in the soil freezes.
### Standards and Guidelines for Communication Sites

**Soil Resistivity Variability and Factors Affecting Soil Resistivity**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Resistivity (Ω·cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>°F</td>
</tr>
<tr>
<td>20</td>
<td>68</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>0 (water)</td>
<td>32 (water)</td>
</tr>
<tr>
<td>0 (ice)</td>
<td>32 (ice)</td>
</tr>
<tr>
<td>-5</td>
<td>23</td>
</tr>
<tr>
<td>-15</td>
<td>14</td>
</tr>
</tbody>
</table>

Source: Soares Book on Grounding and Bonding, 9th addition (ISBN 1890659-36-3).

**Figure B-2** Soil resistivity changes as a function of soil temperature

Because the resistivity of soil is directly affected by its moisture content and temperature, it is reasonable to conclude that the resistance of any grounding electrode system will vary throughout the different seasons of the year. Figure B-3 shows the seasonal variations of the resistance to earth of a grounding electrode.

**Figure B-3** Seasonal variations in grounding electrode resistance

Source: Soares Book on Grounding and Bonding, 9th addition (ISBN 1890659-36-3).
Temperature and moisture content both become more stable as distance below the surface of the earth increases. Therefore, in order to be effective throughout the year, a grounding electrode system should be installed as deep as practical. Best results are achieved when ground rods, or other grounding electrodes, reach permanent moisture.

B.2 TESTING METHODS

Two methods of obtaining soil resistivity data are typically used, as follows:

- Four-point (Wenner) method (See BS 7430:1998, IEEE STD 81, and MIL-HDBK-419A for more information.)
- Random core samples

Where possible, the testing should be performed using the four-point testing method; this is the method described in this specification. The area indicating the lowest soil resistivity will be the optimum location for placement of the grounding (earthing) electrode system. A suggested best practice is to perform the test during different seasons of the year whenever possible. The worst-case measured soil resistivity should then be considered in order to design a grounding electrode system that will meet the resistance design goal throughout the year.

Random core sampling should be used only when the four-point test cannot be accomplished, such as in metropolitan areas, areas where buried metallic objects may cause misleading readings, or where surface area is insufficient for proper test performance. Random core sampling shall be performed by a geotechnical firm. The random core sample test results can then be used in the section “Interpreting Test Results” on page B-10, or provided to an engineering firm so they can design an appropriate grounding electrode system.

NOTE: The same core samples taken for foundation design can also be used for conducting the random core sample testing.

Core samples should be taken from at least five different test areas as shown in Figure B-5 at depths of 1.52, 3, and 6.1 m (5, 10, and 20 ft.).

B.3 SITE PREPARATION CONSIDERATIONS

NOTE: Do not test an adjacent location if the site location is inaccessible when the testing is scheduled. Reschedule the test so it can be done on the site itself.

Soil resistivity tests must be performed on the actual site, after the following preparation and conditions have been met:

- The site has been leveled to where the foundation will be placed.
- Soil added to the site is satisfactorily compressed before conducting the test, so it will behave as undisturbed soil.
- No precipitation has occurred within 72 hours.
B.3.1 Required Test Equipment and Supplies

The required test equipment and supplies for performing a soil resistivity test are as follows:

- Ground (Earth) Resistance Tester designed for four-point testing, including all necessary accessories provided by the manufacturer. Accessories should include:
  - Operator’s manual
  - Four test rods (typically supplied with tester)
    The test rods should be stainless steel, 610 mm (24 in.) maximum length, 16 mm (0.375 in.) diameter, utilizing a preferred surface penetration of 229 mm (9 in.). Test rods typically come with a four-point testing kit, in lengths from 381 mm (15 in.) to 610 mm (24 in.).
  - Four test leads (typically supplied with tester)
    The test leads connect the tester to the test rods. If the leads do not use labels or different colors to correlate the test lead connections between the rods and tester terminals, use tags or four different colors of tape to correlate the connections.

**IMPORTANT:** The connections must be kept in the correct order to maintain symmetry of testing procedures and maintain consistent results.

- Small sledgehammer
- Tape measure
- Safety glasses
- Gloves
- A photocopy of Table B-3 on page B-15. This will be needed to record and keep track of several measurements across the site.

B.3.2 Safety

**WARNING**

Follow the manufacturer’s warning and caution information when using the ground resistance tester. Follow furnished instructions when inserting and removing test rods into soil.

- It is required that personnel attempting to measure the resistivity of earth receive prior formal training on the subject and on its associated safety hazards. All applicable laws, rules and codes regulating the work on electrical systems shall be complied with at all times.
- Make certain the procedure is fully understood before proceeding with test.
B.3.3 PERFORMING SOIL RESISTIVITY TEST

Perform the test at the location where the site will be built. This procedure describes how to obtain test results for various depths, and how to measure the soil resistivity over the entire site.

IMPORTANT: Buried underground metallic objects such as pipes, cables or tanks can provide an alternate path for test current from a soil resistivity meter, resulting in inaccurate measurements. Therefore, do not test in areas with buried underground metallic objects.

B.3.3.1 MEASURING AT VARIOUS DEPTHS

The soil is typically not homogenous from the surface to the depth being tested and resistivity varies at different depths. Because of this, the four-point test (performed at various depths and at various locations throughout the site) is used to provide a composite result of the soil resistivity.

The testing depth of a soil resistivity test is determined by the spacing between the four test rods which correspondingly connect to tester terminals C1, P1, P2, and C2. The recommended practice is to test the soil at various depths in order to determine the best depth for the grounding (earthing) electrode system. For example, if the test rods are 1.52 m (5 ft.) apart, the measurement will be an average of the soil from the surface down to 1.52 m (5 ft.). As the spacing between the rods is increased, results for correspondingly deeper samples are directly obtained. Table B-2 lists the soil depths measured for different rod spacing distances.

**TABLE B-2  SOIL DEPTH MEASURED AS A FUNCTION OF ROD SPACING**

<table>
<thead>
<tr>
<th>Rod Spacing</th>
<th>Soil Depth Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.52 m (5 ft.)</td>
<td>1.52 m (5 ft.)</td>
</tr>
<tr>
<td>3 m (10 ft.)</td>
<td>3 m (10 ft.)</td>
</tr>
<tr>
<td>6.1 m (20 ft.)</td>
<td>6.1 m (20 ft.)</td>
</tr>
<tr>
<td>9.1 m (30 ft.)</td>
<td>9.1 m (30 ft.)</td>
</tr>
<tr>
<td>12.2 m (40 ft.)</td>
<td>12.2 m (40 ft.)</td>
</tr>
</tbody>
</table>
B.3.3.2 Testing Theory and Rod Arrangement

Figure B-4 shows the rod arrangement required for testing. The test requires inserting four test rods into the test area, in a straight line, equally spaced and all at a depth of 229 mm (9 in.). A constant current is injected into the earth from the earth resistance tester through the two outer test rods. The voltage drop resulting from the current flow through the earth is then measured across the inner two test rods. Most testers are designed to provide a direct reading in ohms. This value is then used in one of the following formulas to calculate the soil resistivity ($\rho$) of the tested area.

$$\rho = 191.5 \times A \times R$$

Where:
- $\rho$ = soil resistivity in $\Omega\cdot$cm
- $A$ = Distance between test rods (in feet)
- $R$ = Resistance obtained from tester (in ohms)

OR

$$\rho = 628 \times A \times R$$

Where:
- $\rho$ = soil resistivity in $\Omega\cdot$cm
- $A$ = Distance between test rods (in metres)
- $R$ = Resistance obtained from tester (in ohms)

The calculated soil resistivity is the average soil resistivity between the soil surface and the depth of the soil equivalent to the rod spacing.
B.3.3.3 Samples Required to Develop Accurate Site Resistivity Profile

Because stray currents, buried water pipes, cable sheaths and other factors usually interfere and distort the readings, measurements should be taken along at least three directions. Figure B-5 shows the recommended multiple sampling pattern to develop an accurate profile. Note that the more divergent the samples taken, the more accurate the generated soil model will be.
B.3.3.4 Soil Resistivity Measurement Procedure

Perform the following procedure to obtain soil resistivity readings.

**WARNING**

Follow the manufacturer's warning and caution information when using the ground resistance tester. Follow furnished instructions when inserting and removing test rods into soil.

1. On tester, verify that the jumper strap between the C1 and P1 terminals is disconnected (if applicable).

2. Starting at the “First Test Location” shown in Figure B-5, drive four test rods into the soil to a depth of 229 mm (9 in.), in a straight line, and spaced 1.52 m (5 ft.) apart (as shown in Figure B-4).

   **NOTE:** The test rods must be connected in the order specified in Step 3. If the test rods are connected incorrectly an inaccurate reading will result.

3. Using test leads, connect the C1, P1, P2 and C2 terminals to their respective test rods, as shown in Figure B-4.

4. Turn the tester on. Press the test button and read the display.

   **NOTE:** If the reading is not stable or displays an error indication, double-check the connection and the meter range setting. If the range is correct, try adjusting the test current. An effective way of decreasing the test rod resistance to ground is by pouring water around the rod. The addition of moisture is insignificant; it will only achieve a better electrical connection and will not influence the overall results.
5. Record the measurement obtained in the appropriate “Meter Readings” space on the photocopy of the “Soil Resistivity Worksheet” on page B-15.

6. Remove the test rods from the soil.

7. In the same location on the site and along the same line as previous test, repeat steps 2 through 6 for remaining spacings listed on the Soil Resistivity Worksheet.

8. Prepare to take measurements for the next test location shown in Figure B-5. Repeat steps 2 through 7 for this location.

9. Repeat steps 2 through 8 for all remaining test locations specified in Figure B-5.

10. On the Soil Resistivity Worksheet copy, calculate and record soil resistivity ($\rho$) for each of the 25 readings taken in the steps above.

**B.3.4 INTERPRETING TEST RESULTS**

Depending on the type of grounding electrode system to be installed, proceed to the applicable paragraph below. Test results are interpreted in accordance with MIL-HDBK-419A.

- “Calculating Single Grounding Electrode System Resistance” on page B-10
- “Calculating Multiple Grounding Electrode System Resistance (Electrodes In Straight Line)” on page B-19
- “Multiple Grounding Electrode System Resistance Calculation (Electrodes In Ring Configuration)” on page B-24
- “Calculating Multiple Grounding Electrode System Resistance (Ground Rod Grid Configuration)” on page B-24

**NOTE:** The interpreted test results are typically conservative because the effects of the horizontal connecting conductors (typically ground rings) are not considered in the following calculations. Consideration of the horizontal connecting conductors requires complex calculations that are beyond the scope of this manual. An engineering firm may be required to perform calculations that consider the effects of the horizontal connecting conductors.

**B.3.4.1 CALCULATING SINGLE GROUNDING ELECTRODE SYSTEM RESISTANCE**

For a single grounding (earthing) electrode system, the resistance can be easily calculated using a nomograph. Example calculations are shown in Figure B-6 on page B-12 through C-14.

If calculations show excessive resistance for a given electrode depth and diameter, recalculate substituting a larger diameter electrode and/or deeper electrode depth. In this manner, the proper size and depth of grounding electrode for a particular site can be determined. Figure B-6 Sheet 3 shows an example where grounding is improved by substituting a larger-diameter electrode at a deeper depth.

Perform the following procedure to calculate the resistance of the single grounding electrode.

1. Make a photocopy of Figure B-7 on page B-17.

2. On d scale of nomograph, plot a point corresponding to the diameter of the grounding electrode to be used.
3. On L scale of nomograph, plot a point corresponding to the depth of grounding electrode to be used.

4. Draw a line connecting the d and L points.

5. Plot ρ value from Soil Resistivity Worksheet on the ρ scale of nomograph.

6. Where the line connecting the d and L points intersects the q line, draw a new line from this point to the point plotted on the ρ scale. Extend this line to the R scale. This is the resistance for a single grounding electrode.

B.3.4.2 EXAMPLE WORKSHEET AND NOMOGRAPH

Figure B-6 (sheets 1 through 3) shows example readings and calculations from a completed worksheet and nomograph.

- Sheet 1 shows example readings, as entered from field Ground Resistance Tester measurements and the resulting Soil Resistivity calculations.
- Sheet 2 shows an example of a completed nomograph.
- Sheet 3 shows a second nomograph filled-in with calculations for grounding electrode resistance improvement using a larger-diameter electrode at a deeper depth.
Location “1 of 5” 3 m (10 ft.) spacing is measured on Ground Resistance Tester. In this example, tester reads “2.1 Ω”.

“2.1” is written down in “Meter Readings” column for Location “1 of 5” (10 ft. spacing) in Worksheet.

ρ value for Location “1 of 5” 10 ft spacing is calculated using formula on Worksheet.

ρ value of “4021.5” is written down in “Soil Resistivity Calculations” column for Location “1 of 5” (10 ft spacing) in Worksheet.

<table>
<thead>
<tr>
<th>Location</th>
<th>Spacing (Test Depth)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.52 m (5 ft.)</td>
</tr>
<tr>
<td></td>
<td>3 m (10 ft.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Meter Readings (steps 2 through 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 of 5</td>
</tr>
<tr>
<td>2 of 5</td>
</tr>
<tr>
<td>3 of 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>ρ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 of 5</td>
<td>4021.5</td>
</tr>
<tr>
<td>2 of 5</td>
<td>4308.8</td>
</tr>
<tr>
<td>3 of 5</td>
<td>4021.5</td>
</tr>
</tbody>
</table>

**FIGURE B-6**  **EXAMPLE WORKSHEET AND NOMOGRAPH (SHEET 1 OF 3)**
1. Points corresponding to 5/8-in dia. electrode and 10-ft. depth are plotted on "d" and "L" scales.

2. Line is drawn connecting points on "d" and "L" scales.

3. ρ value from Worksheet is plotted on "ρ" scale (in this example, 4.02 kΩ-cm).

4. Line is drawn connecting the points where "q" scale is intersected by "d-L" line, and the point on "ρ" scale. Line is extended to "R" scale to obtain resistance for electrode (in this example, 15 Ω).

Figure B-6 Example Worksheet and Nomograph (Sheet 2 of 3)
Plotted values for 19 mm (3/4 in.) electrode at 20-ft. depth for same meter reading shows lower electrode resistance (7.5 Ω in this example, vs. 15 Ω in previous example).

FIGURE B-6  EXAMPLE WORKSHEET AND NOMOGRAPH (SHEET 3 OF 3)
## Table B-3 Soil Resistivity Worksheet

<table>
<thead>
<tr>
<th>Location</th>
<th>Spacing (Test Depth)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.52 m (5 ft.)</td>
</tr>
<tr>
<td></td>
<td>3 m (10 ft.)</td>
</tr>
<tr>
<td></td>
<td>6.1 m (20 ft.)</td>
</tr>
<tr>
<td></td>
<td>9.1 m (30 ft.)</td>
</tr>
<tr>
<td></td>
<td>12.2 m (40 ft.)</td>
</tr>
</tbody>
</table>

### Meter Readings (steps 2 through 5)

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 of 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 of 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 of 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 of 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 of 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Soil Resistivity Calculations (step 10)

\[
\rho = 191.5 \times A \times R \\
\rho = \text{soil resistivity in } \Omega \cdot \text{cm} \\
A = \text{Distance between test rods (in feet)} \\
R = \text{Resistance obtained from tester}
\]

OR

\[
\rho = 628 \times A \times R \\
\rho = \text{soil resistivity in } \Omega \cdot \text{cm} \\
A = \text{Distance between test rods (in metres)} \\
R = \text{Resistance obtained from tester}
\]

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 of 5</td>
<td>(\rho)</td>
<td>(\rho)</td>
<td>(\rho)</td>
<td>(\rho)</td>
</tr>
<tr>
<td>2 of 5</td>
<td>(\rho)</td>
<td>(\rho)</td>
<td>(\rho)</td>
<td>(\rho)</td>
</tr>
<tr>
<td>3 of 5</td>
<td>(\rho)</td>
<td>(\rho)</td>
<td>(\rho)</td>
<td>(\rho)</td>
</tr>
<tr>
<td>4 of 5</td>
<td>(\rho)</td>
<td>(\rho)</td>
<td>(\rho)</td>
<td>(\rho)</td>
</tr>
<tr>
<td>5 of 5</td>
<td>(\rho)</td>
<td>(\rho)</td>
<td>(\rho)</td>
<td>(\rho)</td>
</tr>
</tbody>
</table>

Test completed by: ____________________________

Notes: ____________________________

Date: ____________________________

Client / Project: ____________________________

Site Location/ID: ____________________________

Ground Resistance Tester
Model: ____________________________
S/N: ____________________________
Calibration date: ____________________________

Soil Description: ____________________________

Ambient Conditions
Temperature: ____________________________
Present conditions (dry, rain, snow): ____________________________
Date of last precipitation: ____________________________
FIGURE B-7  SOIL RESISTIVITY NOMOGRAPH
THIS PAGE INTENTIONALLY LEFT BLANK.
B.3.4.3 Calculating Multiple Grounding Electrode System Resistance (Electrodes in Straight Line)

For a multiple grounding (earthing) electrode system with multiple parallel electrodes in a straight line (as shown in Figure B-8), the system resistance can be calculated as described in the following procedure.

1. Perform soil resistivity test as described in “Soil Resistivity Measurement Procedure” on page B-9.

2. Using the worst-case value obtained, calculate the resistance of one ground rod as described in “Calculating Single Grounding Electrode System Resistance” on page B-10. Write down this number.

3. Sketch a proposed layout of the ground rod arrangement using equally spaced rods in a line.

**NOTE:** The stipulations regarding rod spacing specified in “Ground Rods” on page 4-11 must be observed when planning rod layout.

4. Make a photocopy of Figure B-9 on page B-21.

5. Using the copy of Combined Resistance Graph (Ground Rods Arranged in Line or Ring), calculate the effective resistance of the proposed layout as follows:

   5.1 Noting the number of rods to be used, locate this number on the Number of Rods axis of the graph.

   5.2 Note the spacing of the rods in the proposed layout in terms of spacing as related to length of rods. In graph, “s=L” is spacing equal to length of rod “s=2L” is spacing equal to twice the length of rod, and so on. Locate the spacing line on graph (s=L, s=2L, s=3L, s=4L) corresponding to proposed spacing.

   5.3 At the point on the graph where the Number of Rods line intersects the appropriate spacing line, note the Combined Resistance number at the left.

   5.4 Multiply the Combined Resistance number by the resistance of a single ground rod noted in step 2 of this procedure. This is the worst-case resistance of the proposed grounding electrode system.

B.3.4.4 Example Layout And Graph

Assuming a layout as shown in Figure B-8 with the following characteristics:

- Eight rods (each of 8-ft. length) are spaced at 4.9 m (16 ft.) points (or “2L” in terms of the graph) along a line.
- Worst-case soil resistivity measurement (step 1 above) is 4021.5 Ω·cm.
- Resistance of single rod tested (step 2 above) is 15 Ω

System resistance is calculated as follows:

1. Using Figure B-14: because eight rods are used, “8” line on Number of Rods in graph is selected.

2. Because rod spacing is 4.9 m (16 ft.), or “2L” of rod length, “s=2L” line on graph is selected.

3. At the intersection of the “8” line and the “s=2L” line, draw a horizontal line to the Combined Resistance axis at left. Note the point where the horizontal line crosses the Combined Resistance axis (in this case, at approximately “18” (or 18% of single rod resistance)).
4. Single rod resistance of $15 \, \Omega$ is then multiplied by 18% ($0.18$) to obtain the effective resistance of the system:

$$15\Omega \times 0.18 = 2.7 \, \Omega$$

In this example, effective overall resistance of the proposed system would be $2.7 \, \Omega$.

**FIGURE B-8** EXAMPLE OF MULTIPLE GROUNDING ELECTRODES IN STRAIGHT LINE
**Figure B-9** Combined Resistance Graph (Ground Rods Arranged in Line or Ring)
Figure B-10 Example Calculation of Ground Rods Arranged in Straight Line

Because rod spacing is 4.9 m (16 ft.), or “2L” of rod length, “s=2L” line on graph is selected.

Line drawn from intersection solves system \( \Omega \) to be 18% of single-rod \( \Omega \).

Because eight rods are used, “8” line on Number of Rods in graph is selected.
B.3.4.5 MULTIPLE GROUNDING ELECTRODE SYSTEM RESISTANCE CALCULATION (ELECTRODES IN RING CONFIGURATION)

For a multiple grounding (earthing) electrode system with multiple electrodes installed in a ring configuration (as shown in Figure B-11), the system resistance is calculated in the same manner as electrodes placed in a straight line.

When planning a ring configuration layout and performing calculations, note the following:

- All rods in the system shall maintain equal or greater separation from adjacent rods.
- The distance between rods shall be figured in a direct path to adjacent rods, not the circumference distance of the ring.

**NOTE:** The stipulations regarding rod spacing specified in “External Building and Tower Ground Ring” on page 4-22 must be observed when planning rod layout.

![Ground rods arranged in ring](image)

**FIGURE B-11  RING CONFIGURATION PLANNING AND RESISTANCE MEASUREMENT CONSIDERATIONS**

B.3.4.6 CALCULATING MULTIPLE GROUNDING ELECTRODE SYSTEM RESISTANCE (GROUND ROD GRID CONFIGURATION)

For a multiple grounding (earthing) electrode system consisting of a ground rod grid configuration (as shown in Figure B-12), the system resistance can be calculated as described in the following procedure.

1. Perform soil resistivity test as described in “Soil Resistivity Measurement Procedure” on page B-9.
2. Using the worst-case value obtained, calculate the resistance of one ground rod as described in “Calculating Single Grounding Electrode System Resistance” on page B-10. Write down this number.
3. Sketch a proposed layout of the ground rod arrangement using equally spaced rods across the proposed area.
NOTE: The stipulations regarding rod spacing as specified in “Ground Rods” on page 4-11 must be observed when planning rod layout.

4. Calculate the area of the proposed grid system in square feet.

NOTE: This procedure requires that grid measurements be entered in square feet. If metric measurements have been made, the measurements must be converted to feet. (See Appendix E for conversion formulas.)

5. Make a photocopy of Figure B-13 on page B-27.

6. Using the copy of Combined Resistance Graph (Ground Rods Arranged in Grid), calculate the effective resistance of the proposed layout as follows:

   6.1 Noting the number of rods to be used, locate this number on the Number of Rods axis of the graph.

   6.2 Note the square footage of the proposed rod layout. Locate the curve on the graph most closely corresponding to the proposed square footage.

   6.3 At the point on the graph where the Number of Rods line intersects the appropriate square footage curve, note the Resistance Ratio number at the left.

   6.4 Multiply the Resistance Ratio number by the resistance of a single ground rod noted in step 2 of this procedure. This is the worst-case resistance of the proposed grounding electrode system.

B.3.4.7 Example Layout and Graph

Assuming a layout as shown in Figure B-12 with the following characteristics:

- 16 rods equally spaced across a 30 × 30 ft. grid (900 sq. ft.).
- Worst-case soil resistivity measurement (step 1 above) is 4021.5 Ω-cm.
- Resistance of single rod tested (step 2 above) is 15 Ω

System resistance is calculated as follows:

1. (See Figure B-14 on page B-29.) Because 16 rods are used, the point corresponding to “16” on Number of Rods in graph is selected. Draw a line vertically from the “16” point on the graph.

2. Because the grid is 900 sq. ft., a point just below the 1,000 sq. ft. curve on graph is plotted on the line drawn on the graph.

3. At the point plotted in the previous step, (intersection of “900” sq. ft. and “16” rods), draw a horizontal line to the Resistance Ratio axis at left. Note the point where the drawn horizontal line crosses Resistance Ratio axis (in this case, at approximately “.17”).

4. The single rod resistance of 15 W is then multiplied by 0.17 to obtain the effective resistance of the system:

   \[ 15\Omega \times 0.17 = 2.55\Omega \]

In this example, the effective overall resistance of the proposed ground system would be 2.55 Ω.
FIGURE B-12 EXAMPLE OF MULTIPLE GROUNDING GROUND ROD GRID CONFIGURATION
Figure B-13 Combined Resistance Graph (Ground Rods Arranged in Grid)
Resistance Ratio (Multiple Rods/One Rod)

Because grid is 900 sq. ft., a point just below 1,000 sq. ft. curve on graph is plotted.

Because 16 rods are used, point corresponding to “16” on Number of Rods in graph is selected.

FIGURE B-14  EXAMPLE CALCULATION OF GROUND ROD GRID CONFIGURATION
B.3.4.8 Calculating Resistance of Complex Ground Rod Systems

Complex ground rod systems consist of multiple subsystems bonded together to form an overall site ground rod system. Figure B-15 on page B-33 shows a typical complex ground rod system.

Resistance of a complex ground rod system can be calculated by breaking down the system into subsystems. Typically, a ground rod system can be broken down into the following individual subsystems:

- Building ground ring
- Tower ground ring
- Tower radial grounding conductors

For a complex ground rod system consisting of the above subsystems or similar multiple subsystems, the overall system resistance can be approximated as described in the following procedure.

**NOTE:** Adjacent subsystems should not be laid out closer than the ground rod spacing distance used within a particular subsystem. This is because as subsystems become closer than this distance, the adjacent subsystems begin to “act” as a single subsystem rather than two subsystems.

1. Perform soil resistivity test as described in “Soil Resistivity Measurement Procedure” on page B-9.
2. Using the worst-case value obtained, calculate the resistance of one ground rod as described in “Calculating Single Grounding Electrode System Resistance” on page B-10. Record this number; it is needed for following calculations.
3. Sketch a proposed layout of the ground rod arrangement using equally spaced rods across the proposed area.

**NOTE:** The stipulations regarding rod spacing as specified in “Ground Rods” on page 4-11 must be observed when planning rod layout.

4. Calculate the resistance of the building ground ring subsystem as described in “Multiple Grounding Electrode System Resistance Calculation (Electrodes In Ring Configuration)” on page B-24. Write down the result.
5. Calculate the resistance of the tower ground ring subsystem as described in “Multiple Grounding Electrode System Resistance Calculation (Electrodes In Ring Configuration)” on page B-24. Write down the result.
6. Calculate the resistance of the tower radial grounding conductor subsystem as follows:
   6.1 Calculate and record the resistance of each **individual** tower radial grounding conductor as described in “Calculating Multiple Grounding Electrode System Resistance (Electrodes In Straight Line)” on page B-19.

**NOTE:** If the radial grounding conductor does not contain ground rods, the resistance to earth of the radial grounding conductor can be calculated as follows:
BURIED HORIZONTAL LENGTH OF WIRE (STRAIGHT) \( D << L \)

\[
R = \frac{\rho}{\pi L} \left[ \ln \left( \frac{2L}{(2aD)^{1/2}} \right) - 1 \right]
\]

\( R \) = RESISTANCE OF ELECTRODE IN OHMS
\( \rho \) = SOIL RESISTIVITY IN METRE-OHMS
\( L \) = WIRE LENGTH IN METRES
\( a \) = WIRE RADIUS IN METRES
\( D \) = WIRE DEPTH IN METRES

6.2 Using the results obtained in above step, calculate the **combined (parallel) resistance of the tower ground radials** as follows:

\[
R_{total} = \frac{1}{\frac{1}{R_{radial 1}} + \frac{1}{R_{radial 2}} + \ldots + \frac{1}{R_{radial n}}}
\]

**NOTE:** The ground rods associated with the tower ground ring are not included in the calculation of the tower radial grounding conductors.

7. Noting the resistances determined for the subsystems, calculate the combined (parallel) resistance of **all of the subsystems** as follows:

- subsystem 1 (building ground ring subsystem; step 4)
- subsystem 2 (tower ground ring subsystem; step 5)
- subsystem 3 (tower ground radial subsystem; step 6)

\[
R_{total} = \frac{1}{\frac{1}{R_{subsystem 1}} + \frac{1}{R_{subsystem 2}} + \frac{1}{R_{subsystem 3}}}
\]

**NOTE:** Total resistance does not include incidental influence from site fencing, buried fuel tanks, or other objects not included in these calculations. More complex grounding systems, or highly accurate results where other objects exist, will require the assistance of an appropriate engineering consultant.
B.3.4.9 **EXAMPLE CALCULATION OF COMPLEX SYSTEM**

Assuming a layout as shown in Figure B-15 with the following characteristics:

- Worst-case soil resistivity measurement (step 1 above) is 4021.5 Ω-cm.
- Building ground ring (step 4 above) using four rods, each with a resistance of 15 Ω. Building ground ring subsystem calculates to approximately 4.35 Ω.
- Tower ground ring (step 5 above) using three rods, each with a resistance of 15 Ω. Tower ground ring subsystem calculates to approximately 5.55 Ω.
- Tower radial grounding conductor subsystem (step 6 above) as shown in Figure B-15. Total resistance of this subsystem is as follows:
  - Radial “A” has three ground rods. Resistance of this radial calculates to approximately 5.55 Ω.
  - Radial “B” has two ground rods. Resistance of this radial calculates to approximately 8.1 Ω.
  - Radial “C” has two ground rods. Resistance of this radial calculates to approximately 8.1 Ω.

**Tower ground radial calculates to 2.34 Ω**, as shown below using the formula provided in step 6:

\[
R_{\text{tower radial}} = 2.34 \Omega = \frac{1}{1/(5.55 \Omega) + 1/(8.1 \Omega) + 1/(8.1 \Omega)}
\]

Overall system resistance is calculated as follows:

1. The individual resistances of the three subsystems are noted:
   - **Building ground ring** = 4.35 Ω
   - **Tower ground ring subsystem** = 5.55 Ω
   - **Tower ground radial** = 2.34 Ω

2. The combined (parallel) resistance of all of the subsystems is now calculated as follows:

\[
R_{\text{total}} = 1.19 \Omega = \frac{1}{1/(4.35 \Omega) + 1/(5.55 \Omega) + 1/(2.34 \Omega)}
\]

In this example, the calculated effective overall resistance of the proposed system would be **1.19 Ω**.
A: Grounding Radials
B. Tower Ground Bus Bar and Down Conductor
C. Generator Grounding Conductor
D. Buried Fuel Tank Grounding Conductor
E. External Ground Bus Bar
F. Shelter Ground Ring
G. Fence Grounding Conductor
H. Ground Ring Bonding Conductors (2 minimum)
I. Tower Ground Ring
J. Earthing Electrodes (Ground Rods)

**FIGURE B-15  TYPICAL COMPLEX GROUNDING ELECTRODE SYSTEM**
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