

Chapter 6

Soil Resistivity Measurement

6.1 Introduction

Different types of soil and its characteristics have been discussed in Chap. 4. The value of the soil resistivity is mainly dependent on its properties. Soil resistivity measurement is an important factor in finding the best location for any grounding system. Based on the measurement results, new grounding systems are installed for the power generating station, substation, transmission tower, distribution pole, telephone exchange, industry, commercial and residential buildings.

Nowadays, most of the power utility companies are installing their transmission lines, water and gas pipelines at the same corridor to reduce the land use. The exact value of soil resistivity is very important for the underground pipelines. These underground pipelines are not always parallel with the transmission lines. Sometimes, it runs with different angles with the transmission lines. Therefore, more soil resistivity measurements are need to be carried out at different places. Generally, lower soil resistivity increases the corrosion of underground pipelines. The corrosion ratings of different soil resistivity [1, 2] are shown in Table 6.1.

Basically, the current flow in the underground pipelines increases the corrosion. The sandy soil has a high soil resistivity so its corrosion rating is low. Whereas clay, silt and garden soils have low resistivity which have a high corrosion rating. In this chapter, different methods of soil resistivity measurement will be discussed.

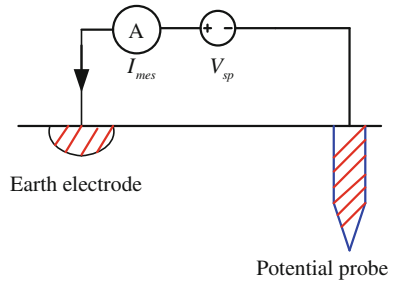
6.2 Two-Pole Method

In this method, a voltage source is connected between a hemisphere earth electrode and an auxiliary probe or potential probe as shown in Fig. 6.1. An ammeter is connected in series with the voltage source to measure the current. For a specific supply voltage and measured current, the resistance can be determined as,

Table 6.1 Soil resistivity with corrosion rating

Soil resistivity ($\Omega\text{-m}$)	Corrosion rating
>200	Essentially non-corrosive
100–200	Mildly corrosive
50–100	Moderately corrosive
30–50	Corrosive
10–30	Highly corrosive
<10	Extremely corrosive

Fig. 6.1 Earth electrode with potential probe



$$R_E = \frac{V_{sp}}{I_{mes}} \tag{6.1}$$

For a hemisphere earth electrode with a radius r , the expression of ground resistance is,

$$R_E = \frac{\rho}{2\pi r} \tag{6.2}$$

Then, the soil resistivity can be determined as,

$$\rho = 2\pi r R_E \tag{6.3}$$

This method is easy to measure the soil resistivity at any small space. In this case, fluke 1625 m can be used to perform the soil resistivity measurement. The connection diagram of two-pole method for the soil resistance measurement is shown in Fig. 6.2.

6.3 Four-Pole Equal Method

In 1915, an American Geologist Dr. Frank Wenner of US Bureau of Standard introduced four-pole equal method to measure the soil resistivity. According to his name, this method is also known as Wenner method. The overall setup for the

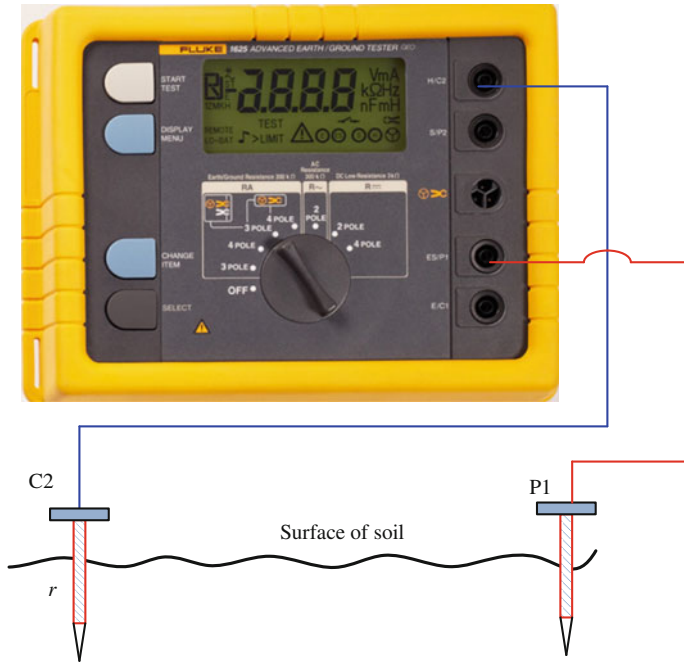


Fig. 6.2 Connection diagram of two-pole method [3]

four-pole equal method is shown in Fig. 6.3. In this method, four equidistant probes are inserted into the soil on a straight line as shown in Fig. 6.3. Then the current terminals (C1 and C2) of the advanced earth testing meter, fluke 1625 are connected to the two outer probes, and the potential probing terminals (P1 and P2) are connected to the two inner probes. Then press the start button of the meter which injects the current into the soil through the current probes and the resulting voltage is measured across the potential probes (inner probes).

According to Ohms law, the meter calculates the soil resistance, and then displays the soil resistance-value. From the measured resistance-value, soil resistivity is calculated using the following formulae,

$$\rho = \frac{4\pi a R_E}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{2a}{\sqrt{2a^2 + 4b^2}}} \tag{6.4}$$

As shown in Fig. 6.3, a is the distance between two adjacent probes, and b is the length of the probe (probe-depth) inserted into the soil. If b (In general, $b = 4a$) is very large compared to a , Eq. (6.4) reduces to,

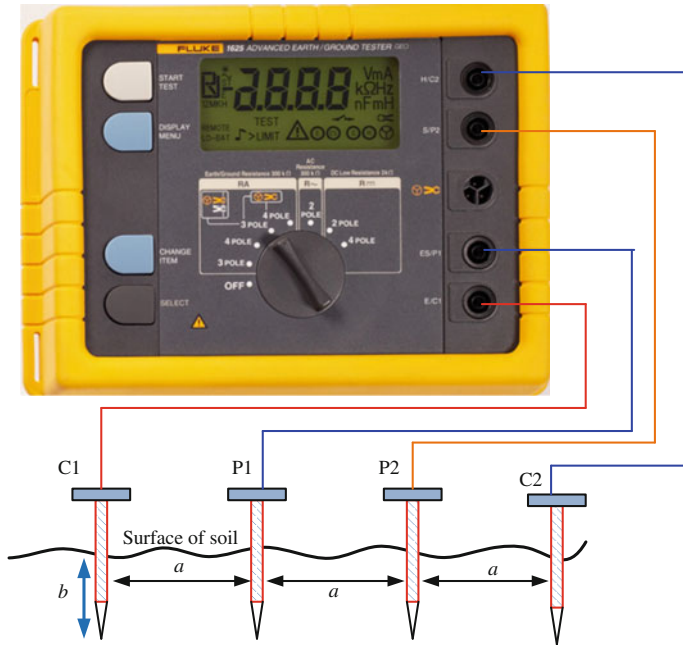


Fig. 6.3 Connection diagram of four poles method [3]

$$\rho = 4\pi aR_E \tag{6.5}$$

If b is very small ($b \ll a$) compared to a , Eq. (6.4) reduces to,

$$\rho = \frac{4\pi aR_E}{1 + 2 - 1} \tag{6.6}$$

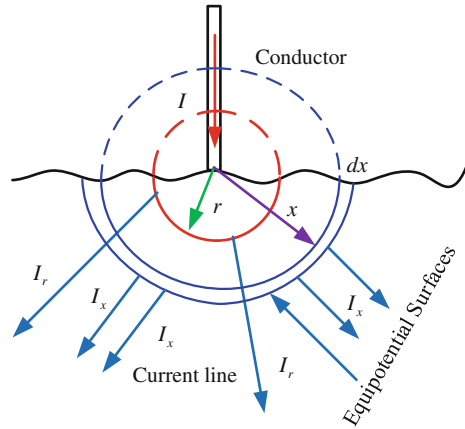
$$\rho = 2\pi aR_E \tag{6.7}$$

During the measurement, the distance between the adjacent probes may be considered to have a value between 1 and 50 ft. This worth nothing that this adjacent distance depends on the available free space near the grounding system.

6.4 Derivation of Resistivity

One-half of a sphere is inserted into the soil as shown in Fig. 6.4 where the buried part forms a hemisphere. A current I is inserted into the soil whose resistivity is ρ and it is distributed to the ground. The current density at the surface of the hemisphere is,

Fig. 6.4 Current in the soil through hemisphere



$$J = \frac{1}{A} = \frac{I}{2\pi r^2} \tag{6.8}$$

The current density at any distance x from the center of the hemisphere is,

$$J(x) = \frac{I}{2\pi x^2} \tag{6.9}$$

The electric field at any distance x from the center of the hemisphere can be determined as,

$$E(x) = \rho J(x) \tag{6.10}$$

Substituting Eq. (6.9) into Eq. (6.10) yields,

$$E(x) = \frac{\rho I}{2\pi x^2} \tag{6.11}$$

The potential difference from the center to earth can be determined as,

$$V_x = \int_r^x E(x) dx \tag{6.12}$$

Substituting Eq. (6.11) into Eq. (6.12) yields,

$$V_x = \int_r^x \frac{\rho I}{2\pi x^2} dx \tag{6.13}$$

$$V_x = -\frac{\rho I}{2\pi} \left[\frac{1}{x} \right]_r^x \quad (6.14)$$

$$V_x = -\frac{\rho I}{2\pi} \left[\frac{1}{r} - \frac{1}{x} \right] \quad (6.15)$$

If $x = \infty$, then the expression of potential difference can be modified as,

$$V_x = \frac{\rho I}{2\pi r} \quad (6.16)$$

The expression of the soil resistance is,

$$R_E = \frac{V_{12}}{I} = \frac{\rho}{2\pi r} \quad (6.17)$$

Then the expression of soil resistivity can be written as,

$$\rho = 2\pi r R_E \quad (6.18)$$

Four probes are considered as spheres and they are placed on a straight line with an equal separation distance a as shown in Fig. 6.5. The current enters through the first sphere and is distributed radially into the soil. This current will come out of the sphere 4. The distances of the spheres 2 and 3 from the sphere 1 are a and $2a$, respectively. According to Eq. (6.15), the potential at the sphere 2 due to the current flowing through the sphere 1 can be written as,

$$V_2 = \frac{\rho I}{4\pi} \left[\frac{1}{a} - \frac{1}{2a} \right] \quad (6.19)$$

Similarly, the potential at the sphere 3 due to the current flowing out of the sphere 4 is,

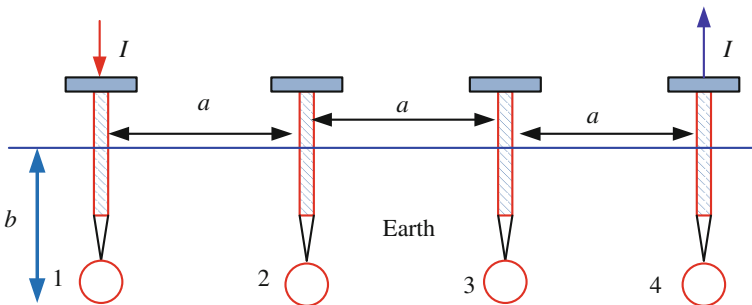


Fig. 6.5 Four spheres in the soil

$$V_3 = \frac{\rho I}{4\pi} \left[\frac{1}{2a} - \frac{1}{a} \right] \tag{6.20}$$

The potential difference between the spheres 2 and 3 is,

$$V = V_2 - V_3 \tag{6.21}$$

Substituting Eqs. (6.19) and (6.20) into Eq. (6.21) yields,

$$V = \frac{\rho I}{4\pi} \left[\frac{1}{a} - \frac{1}{2a} \right] - \frac{\rho I}{4\pi} \left[\frac{1}{2a} - \frac{1}{a} \right] \tag{6.22}$$

$$V = \frac{\rho I}{4\pi} \left[\frac{1}{a} - \frac{1}{2a} - \frac{1}{2a} + \frac{1}{a} \right] \tag{6.23}$$

$$V = \frac{\rho I}{4\pi} \left[\frac{2}{a} - \frac{1}{a} \right] \tag{6.24}$$

$$\rho = 4\pi a \frac{V}{I} = 4\pi a R_E \tag{6.25}$$

Two conductors are placed on the top soil surface and four conductors are placed on a straight line inside the soil that forms the bottom soil surface as shown in Fig. 6.6.

From Fig. 6.6, the following equations can be written as,

$$r_{12} = r_{34} = a \tag{6.26}$$

$$r_{13} = r_{42} = 2a \tag{6.27}$$

$$r_{53} = r_{62} = \sqrt{4a^2 + 4b^2} \tag{6.28}$$

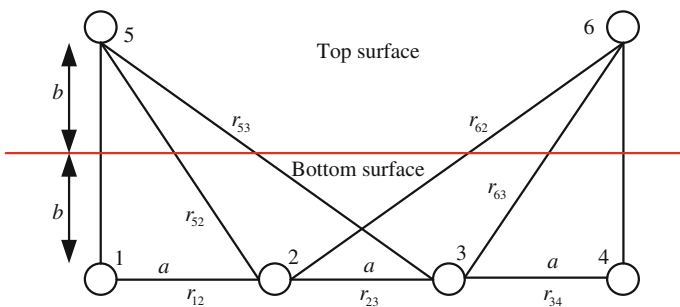


Fig. 6.6 Conductors at the top and bottom surface of the soil

$$r_{52} = r_{63} = \sqrt{a^2 + 4b^2} \quad (6.29)$$

Initially, consider the current enters into the conductor 1 and leaving out of the conductor 4. The potentials at the conductors 2 and 3 are V_a and V_b , respectively. According to Eq. (6.15), the expression of these potentials can be written as,

$$V_a = \frac{\rho I}{4\pi} \left[\frac{1}{r_{12}} - \frac{1}{r_{24}} \right] \quad (6.30)$$

$$V_b = \frac{\rho I}{4\pi} \left[\frac{1}{r_{13}} - \frac{1}{r_{43}} \right] \quad (6.31)$$

Substituting Eqs. (6.26) and (6.27) into Eqs. (6.30) and (6.31) yields,

$$V_a = \frac{\rho I}{4\pi} \left[\frac{1}{a} - \frac{1}{2a} \right] = \frac{\rho I}{4\pi} \frac{1}{2a} \quad (6.32)$$

$$V_b = \frac{\rho I}{4\pi} \left[\frac{1}{2a} - \frac{1}{a} \right] = \frac{\rho I}{4\pi} \left(-\frac{1}{2a} \right) \quad (6.33)$$

The potential differences between the conductors 2 and 3 is,

$$V_m = V_a - V_b \quad (6.34)$$

Substituting Eqs. (6.32) and (6.33) into Eq. (6.34) yields,

$$V_m = \frac{\rho I}{4\pi} \frac{1}{2a} - \frac{\rho I}{4\pi} \left(-\frac{1}{2a} \right) \quad (6.35)$$

$$V_m = \frac{\rho I}{4\pi} \left(\frac{1}{2a} + \frac{1}{2a} \right) \quad (6.36)$$

$$V_m = \frac{\rho I}{4\pi} \frac{1}{a} \quad (6.37)$$

Again, consider the current is entering in the conductor 5 and leaving out of the conductor 6. In this case, the potentials at the conductors 2 and 3 are,

$$V_c = \frac{\rho I}{4\pi} \left[\frac{1}{r_{52}} - \frac{1}{r_{62}} \right] \quad (6.38)$$

$$V_d = \frac{\rho I}{4\pi} \left[\frac{1}{r_{53}} - \frac{1}{r_{63}} \right] \quad (6.39)$$

Again, the potential difference between the conductors 2 and 3 is,

$$V_n = V_c - V_d \quad (6.40)$$

Substituting Eqs. (6.38) and (6.39) into Eq. (6.40) yields,

$$V_n = \frac{\rho I}{4\pi} \left[\frac{1}{r_{52}} - \frac{1}{r_{62}} - \frac{1}{r_{53}} + \frac{1}{r_{63}} \right] \quad (6.41)$$

Substituting Eqs. (6.28) and (6.29) into Eqs. (6.41) yields,

$$V_n = \frac{\rho I}{4\pi} \left[\frac{1}{\sqrt{a^2 + 4b^2}} - \frac{1}{\sqrt{4a^2 + 4b^2}} - \frac{1}{\sqrt{4a^2 + 4b^2}} + \frac{1}{\sqrt{a^2 + 4b^2}} \right] \quad (6.42)$$

$$V_n = \frac{\rho I}{4\pi} \left[\frac{2}{\sqrt{a^2 + 4b^2}} - \frac{2}{\sqrt{4a^2 + 4b^2}} \right] \quad (6.43)$$

Total potential difference for both cases is,

$$V = V_m + V_n \quad (6.44)$$

Substituting Eqs. (6.37) and (6.43) into Eq. (6.44) yields,

$$V = \frac{\rho I}{4\pi} \left[\frac{1}{a} + \frac{2}{\sqrt{a^2 + 4b^2}} - \frac{2}{\sqrt{4a^2 + 4b^2}} \right] \quad (6.45)$$

$$V = \frac{\rho I}{4\pi a} \left[1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{2a}{\sqrt{4a^2 + 4b^2}} \right] \quad (6.46)$$

$$\rho = \frac{V}{I} \frac{4\pi a}{\left(1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{2a}{\sqrt{4a^2 + 4b^2}} \right)} \quad (6.47)$$

$$\rho = \frac{4\pi a R_E}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{2a}{\sqrt{4a^2 + 4b^2}}} \quad (6.48)$$

Equation (6.48) can be modified with respect to different relationships between a and b as discussed earlier.

Example 6.1 A soil resistivity measurement is carried out near a power station using the Wenner four poles equal method. The six readings of soil resistance were

taken during the measurement using the Fluke 1625 earth tester equipment. The readings are recorded at 1, 2, 3, 4, 5 and 6 m intervals of the probe distance. The corresponding soil resistance were measured to be 35, 18, 13, 11.2, 10.2 and 13 Ω , respectively. Determine the soil resistivity and plot it with respect to the probe distance.

Solution

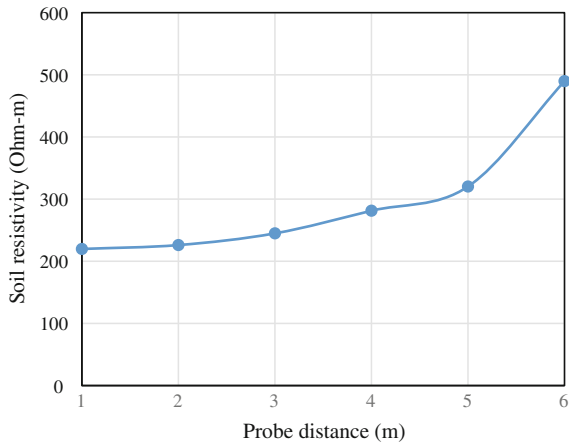
The value of the soil resistivity can be calculated as,

$$\begin{aligned}\rho &= 2\pi aR_e \\ \rho_1 &= 2\pi \times 1 \times 35 = 219.8 \Omega\text{-m} \\ \rho_2 &= 2\pi \times 2 \times 18 = 226.08 \Omega\text{-m} \\ \rho_3 &= 2\pi \times 3 \times 13 = 244.92 \Omega\text{-m} \\ \rho_4 &= 2\pi \times 4 \times 11.2 = 281.34 \Omega\text{-m} \\ \rho_5 &= 2\pi \times 5 \times 10.2 = 320.28 \Omega\text{-m} \\ \rho_6 &= 2\pi \times 6 \times 13 = 489.84 \Omega\text{-m}\end{aligned}$$

The plot of soil resistivity with the probe distance is shown in Fig. 6.7.

Example 6.2 F. Wenner four poles equal method is used to measure the soil resistivity near a 66/11 kV substation using a Fluke 1625 earth tester. The readings are recorded at 1, 2, 3, 4 and 5 m intervals of the probe distance. The corresponding soil resistance were measured to be 16.4, 5.29, 3.05, 1.96 and 1.36 Ω , respectively. Calculate the average soil resistivity in that substation.

Fig. 6.7 Variation of soil resistivity with probe istance



Solution

The value of the soil resistivity can be calculated as,

$$\begin{aligned}\rho &= 2\pi a R_e \\ \rho_1 &= 2\pi \times 1 \times 16.4 = 103 \Omega\text{-m} \\ \rho_2 &= 2\pi \times 2 \times 5.29 = 66.5 \Omega\text{-m} \\ \rho_3 &= 2\pi \times 3 \times 3.05 = 57.5 \Omega\text{-m} \\ \rho_4 &= 2\pi \times 4 \times 1.96 = 49.3 \Omega\text{-m} \\ \rho_5 &= 2\pi \times 5 \times 1.26 = 42.7 \Omega\text{-m}\end{aligned}$$

The average value of the soil resistivity can be determined as,

$$\rho_{av} = \frac{\rho_1 + \rho_2 + \rho_3 + \rho_4 + \rho_5}{5} = \frac{103 + 66.5 + 57.5 + 49.3 + 42.7}{5} = 63.8 \Omega\text{-m}$$

Practice problem 6.1

The soil resistivity measurement is carried out near a power station at 1, 2, 3, 4, 5 and 6 m intervals of the probe distance using F. Wenner four poles equal method. The corresponding soil resistance were measured to be 16, 3.5, 2.6, 2.01, 1.56 and 1.02 Ω , respectively. Find the soil resistivity and plot it with respect to the probe distance.

Practice problem 6.2

F. Wenner four poles equal method is used to measure the soil resistivity near an 11/69 kV power station using a Fluke 1625 earth tester. The readings are recorded at 1, 2, 3, 4 and 5 m intervals of the probe distance. The corresponding soil resistance were measured to be 12.4, 3.25, 2.95, 1.86 and 0.98 Ω , respectively. Determine the average soil resistivity in that substation.

6.5 Lee's Partitioning Method

Lee introduced a method to measure the soil resistivity by partitioning the potential probes. According to his name, this method is known as Lee's partitioning method. In this method, five probes are used on a straight line as shown in Fig. 6.8. The current enters into the first probe and coming out through the fifth probe. In each measurement, four probes are used. The potentials V_2 and V_3 , at the probes 2 and 3 are,

$$V_2 = \frac{\rho I}{2\pi} \left[\frac{1}{a} - \frac{1}{2a} \right] = \frac{\rho I}{4\pi a} \quad (6.49)$$

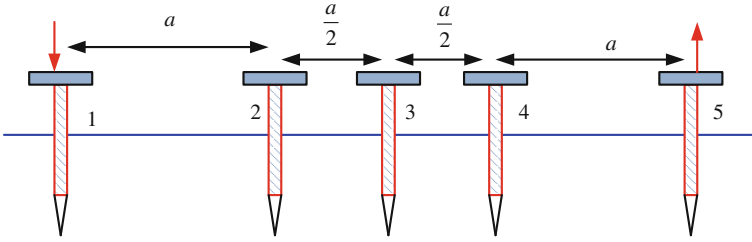


Fig. 6.8 Schematic of Lee's method

$$V_3 = \frac{\rho I}{2\pi} \left[\frac{1}{a+0.5a} - \frac{1}{a+0.5a} \right] = 0 \quad (6.50)$$

The potential difference between the probes 2 and 3 is,

$$V_{23} = V_2 - V_3 = \frac{\rho I}{4\pi a} - 0 \quad (6.51)$$

$$\rho = 4\pi a \frac{V_{23}}{I} = 4\pi a R_{23} \quad (6.52)$$

Similarly, the potential at probes 4 can be written as,

$$V_4 = \frac{\rho I}{2\pi} \left[\frac{1}{2a} - \frac{1}{a} \right] = \frac{\rho}{2\pi} \left(-\frac{1}{2a} \right) \quad (6.53)$$

The potential difference between the probes 3 and 4 is,

$$V_{34} = V_3 - V_4 = 0 - \frac{\rho}{4\pi} \left(-\frac{1}{2a} \right) \quad (6.54)$$

$$\rho = 4\pi a \frac{V_{34}}{I} = \pi a R_{34} \quad (6.55)$$

If the values of the soil resistivity of the two measurements are the same then the soil is considered to be homogeneous.

Example 6.3 Lee's portioning method is used to measure the soil resistivity of a substation. The resistances are measured to be 3Ω between the probes 2 and 3, 2.95Ω between the probes 3 and 4. Determine the soil resistivity if the probe separation distance is 2 m in both cases.

Solution

The value of the soil resistivity can be calculated as,

$$\rho = 4\pi a R_{23} = 4\pi \times 2 \times 3 = 75.4 \Omega\text{-m}$$

$$\rho = 4\pi a R_{34} = 4\pi \times 2 \times 2.95 = 74.14 \Omega\text{-m}$$

In this case, the soil is homogeneous.

Practice problem 6.3

The resistances are measured to be 1.54Ω between the probes 2 and 3, 2.25Ω between the probes 3 and 4 using Lee's portioning method. Find the soil resistivity if the probe separation distance is 1 m in both cases.

6.6 Sided Probe System

In Wenner equal probe system, all the probes along with the connection wires need to be moved for each measurement. Therefore, this method is laborious. In sided probe system, only two probes need to be moved instead of all four probes. The outer second current probes should be placed far away so that the potential difference between the inner probes can be neglected due to the current coming out through it. The current is entering into probe 1 and coming out of probe 4 as shown in Fig. 6.9.

The potential difference between the probes 2 and 3 due to current entering into probe 1 can be written as,

$$V_{23} = \frac{\rho I}{2\pi} \left[\frac{1}{a} - \frac{1}{a+b} \right] \quad (6.56)$$

$$V_{23} = \frac{\rho I}{2\pi} \left[\frac{a+b-a}{a(a+b)} \right] \quad (6.57)$$

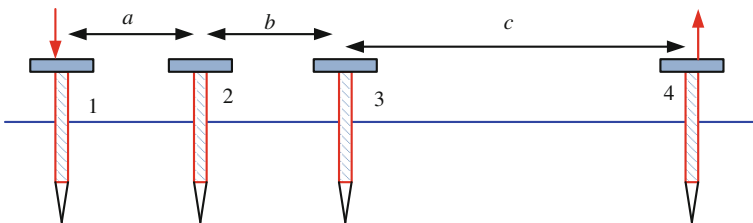


Fig. 6.9 Schematic of sided probe system

$$\rho = 2\pi a \frac{(a+b)}{b} \frac{V_{23}}{I} \quad (6.58)$$

$$\rho = 2\pi a \frac{(a+b)}{b} R_E \quad (6.59)$$

The potential difference between the probes 2 and 3 due to current coming out of probe 4 can be written as,

$$V_{23} = \frac{\rho I}{2\pi} \left[\frac{1}{c} - \frac{1}{b+c} \right] \quad (6.60)$$

$$V_{23} = \frac{\rho I}{2\pi} \left[\frac{b+c-c}{c(b+c)} \right] \quad (6.61)$$

$$\rho = 2\pi c \frac{(b+c)}{b} \frac{V_{23}}{I} \quad (6.62)$$

$$\rho = 2\pi c \frac{(b+c)}{b} R_E \quad (6.63)$$

Dividing Eq. (6.63) by (6.59) yields,

$$1 = \frac{c(b+c)}{a(a+b)} \quad (6.64)$$

If distances a and c are very large compared to b , then Eq. (6.64) reduces as,

$$1 = \frac{c(c)}{a(a)} \quad (6.65)$$

$$\frac{c^2}{a^2} = 1 \quad (6.66)$$

From Eq. (6.66), it is assumed that the ratio of the distance between the potential probe 3 and the current probe 4 to the distance between the current probe 1 and the potential probe 2 is equal or less than 1%. Based on this argument, Eq. (6.66) can be written as,

$$\frac{c^2}{a^2} > 100 \quad (6.67)$$

$$c > 10a \quad (6.68)$$

The main drawback of this method is more spatial distance required compared to the Wenner method to complete the soil resistivity measurement.

6.7 Schlumberger Method

In USA and Europe, Schlumberger method was most popular from 1960 to 1990. In this method, two current probes C1 and C2 are placed on the outside and two potential probes P1 and P2 are placed on the inside of the overall setup as shown in Fig. 6.10. The outer current probes need to be moved symmetrically. However, the potential probes are never moved.

Practically, the ratio of the separation distance of potential probes to the separation distance between the current probes should be one fifth or less. In other words, the distance between the current probes should be four or five times the separation distance between the potential probes. Mathematically, it can be written as,

$$\frac{c}{d} \leq \frac{1}{5} \tag{6.69}$$

This method saves some measurement time due to less movement of the probes. However, Wenner method is more straight forward and simpler than the others method. As shown in Fig. 6.11, the fluke 1625 earth tester is used to insert the current into the soil through the current probe C1.

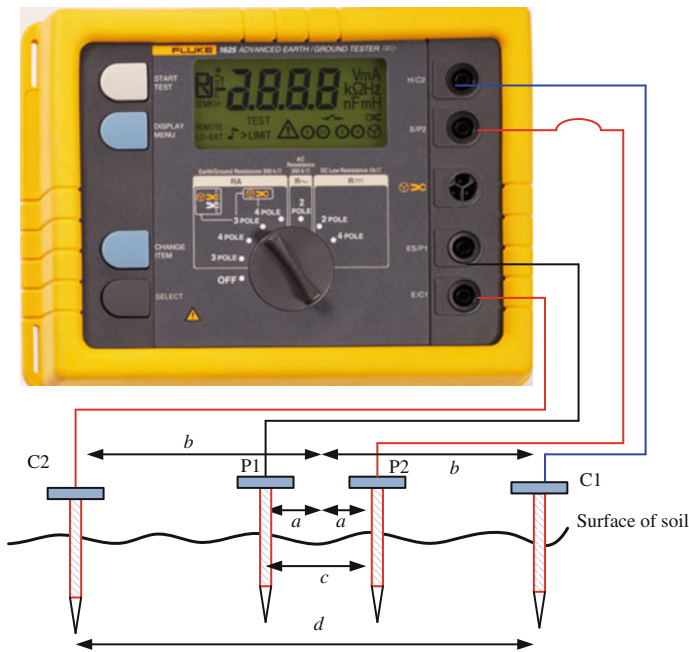


Fig. 6.10 Schematic Schlumberger method [3]

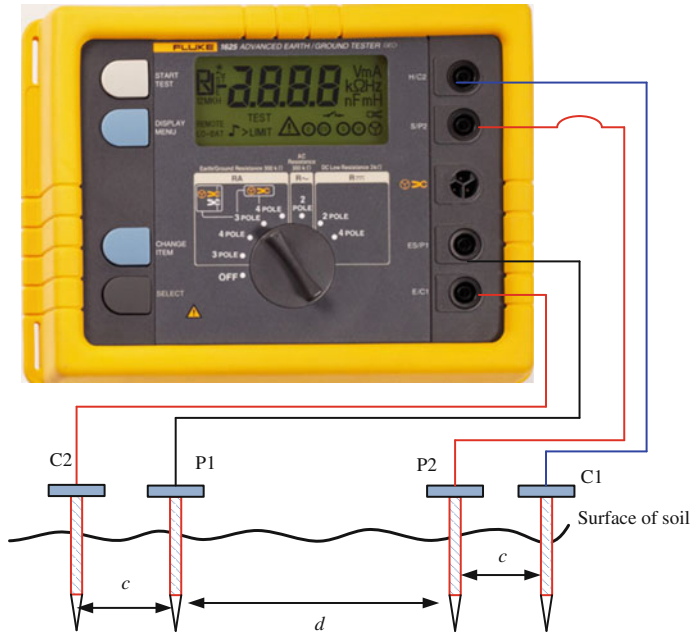


Fig. 6.11 Schematic Schlumberger method for different approach [3]

This current is coming out from the soil through the current probe C2. In this case, the potentials at P1 and P2 are,

$$V_{P1} = \frac{\rho I}{2\pi} \left[\frac{1}{b-a} - \frac{1}{b+a} \right] \tag{6.70}$$

$$V_{P2} = \frac{\rho I}{2\pi} \left[\frac{1}{b+a} - \frac{1}{b-a} \right] \tag{6.71}$$

The potential difference between points P1 and P2 is,

$$V = V_{P1} - V_{P2} \tag{6.72}$$

Substituting Eqs. (6.70) and (6.71) into Eq. (6.72) yields,

$$V = \frac{\rho I}{2\pi} \left[\frac{1}{b-a} - \frac{1}{b+a} - \frac{1}{b+a} + \frac{1}{b-a} \right] \tag{6.73}$$

$$\frac{V}{I} = \frac{4a\rho}{2\pi} \frac{1}{b^2 - a^2} \tag{6.74}$$

$$R_E = \frac{4a\rho}{2\pi} \frac{1}{b^2 - a^2} \quad (6.75)$$

$$\rho = 2\pi R_E \frac{b^2 - a^2}{4a} \quad (6.76)$$

$$\rho = 2\pi a R_E \frac{b^2 - a^2}{4a^2} \quad (6.77)$$

$$\rho = 2\pi a R_E \frac{\frac{b^2}{a^2} - \frac{a^2}{a^2}}{4} \quad (6.78)$$

$$\rho = 2\pi a R_E \frac{\left(\frac{b}{a}\right)^2 - 1}{4} \quad (6.79)$$

$$\rho = 2\pi a R_E \frac{(\alpha)^2 - 1}{4} \quad (6.80)$$

where $\alpha = \frac{b}{a}$. If the value of α is equal to 3, then Eq. (6.80) reduces to the following expression:

$$\rho = 4\pi a R_E \quad (6.81)$$

Equation (6.81) is same as the Wenner equation when the depth of the probe into the soil is very large compared to the adjacent distance between any two probes. The Schlumberger unequal method for soil resistivity measurement can be carried out if there is no physical barrier or obstruction of buried the probes. Figure 6.11 shows the Schlumberger unequal method for alternative expression of soil resistivity. The current is coming out of the soil through the current probe C2. In this case, the expressions of potential at P1 and P2 are,

$$V_{P1} = \frac{\rho I}{2\pi} \left[\frac{1}{c} - \frac{1}{c+d} \right] \quad (6.82)$$

$$V_{P2} = \frac{\rho I}{2\pi} \left[\frac{1}{c+d} - \frac{1}{c} \right] \quad (6.83)$$

Substituting Eqs. (6.82) and (6.83) into Eq. (6.72) yields the potential difference,

$$V = \frac{\rho I}{2\pi} \left[\frac{1}{c} - \frac{1}{c+d} - \frac{1}{c+d} + \frac{1}{c} \right] \quad (6.84)$$

$$V = \frac{\rho I}{2\pi} \left[\frac{2}{c} - \frac{2}{c+d} \right] \quad (6.85)$$

$$V = \frac{2\rho I}{2\pi} \left[\frac{c+d-c}{c(c+d)} \right] \quad (6.86)$$

$$\frac{V}{I} = \frac{\rho}{2\pi} \frac{d}{c(c+d)} \quad (6.87)$$

$$R_E = \frac{\rho}{2\pi} \frac{d}{c(c+d)} \quad (6.88)$$

$$\rho = 2\pi R_E \frac{c(c+d)}{d} \quad (6.89)$$

Example 6.4 The Schlumberger unequal method is used to measure the soil resistivity of a substation. The resistance of the soil is measured to be 6 Ω by setting a distance of 1 m between the current and the potential probes. Calculate the soil resistivity if the two potential probes' separation distance is 2 m.

Solution

The value of the soil resistivity can be determined as,

$$\rho = 2\pi R_E \frac{c(c+d)}{d} = 2\pi \times 6 \times 1 \frac{(1+2)}{2} = 56.55 \Omega\text{-m}$$

Practice problem 6.4

The resistance of the soil is measured to be 8 Ω using the Schlumberger unequal method by setting a distance of 1.5 m between the current probe and the potential probe. Determine the soil resistivity if the two potential probes' separation distance is 2 m.

6.8 Different Terms in Grounding System

Different grounding system parameters including ground, grounding, ground current, ground electrode, grounding system, ground resistance, ground impedance, ground grid, ground potential rise, step and touch potentials are discussed below.

Ground: A conducting connection by which an electrical device or component is connected to the earth is known as ground. It is obtained by ground electrode discussed later.

Grounding: It is often known as grounded. A grounding or grounded is a continuous conductive path which can carry any magnitudes of fault currents.

Ground current: The value of the current that either flow into the soil or out of the soil is known as ground current.

Ground electrode: It is copper rod or plate which is driven into the earth or soil to provide a reliable conductive path to the ground. It is also known as earth electrode.

Grounding system: The combination of the ground electrode, ground plate, clamps, ground clips and connecting conductors is known as grounding system.

Ground resistance: The impedance (Z_R) between a ground electrode, ground plate and the remote earth is known as the ground resistance (R_g).

$$Z_R = R_g + j0 \quad (6.90)$$

Ground impedance: The phasor sum of the resistance (R_g) and the reactance (X_g) between a ground electrode, ground plate and the remote earth is known as the ground impedance.

$$Z_R = R_g + jX_g \quad (6.91)$$

Remote earth: The resistance between one point and a distant point on the earth is known as remote earth. A ground resistance is measured using an earth electrode at a distance of 15 ft. Then, the remote earth measurement will be carried out at any point more than 30 ft of the first measurement.

Maximum grid current: The product of the decrement factor (D_f) and the rms maximum symmetrical current (I_g) is known as maximum grid current (I_G).

$$I_G = D_f \times I_g \quad (6.92)$$

Ground potential rise: The ground potential rise (GPR) is an important parameter in the grounding system. The product of the fault current flowing into the ground through the transmission tower and the resistance to the ground of the grounding system is known as the ground potential rise. Mathematical expression of the GPR with respect to the remote earth is,

$$GPR = I_f R_g = I_G R_g \quad (6.93)$$

6.9 Touch and Step Potentials

There are different types of faults that may occur at the substation, transmission and distribution lines. These are single line to ground fault, line to line fault, double line to ground fault. Due to the presence of these faults, the substation fence and other nearby metallic objects may get energized with an unexpected voltage. This energized metallic structure discharges current into the ground if a person touches it as shown in Fig. 6.12. The awareness of touch and step potentials are very important to the personnel who will be working at the substation and transmission tower. Touch potential is the potential difference between his hand and feet of a person in contact with the energized object. This voltage could be dangerous for the person. The touch potential could be nearly the full voltage across the grounded object if that object is grounded at a point remote from the place where the person is

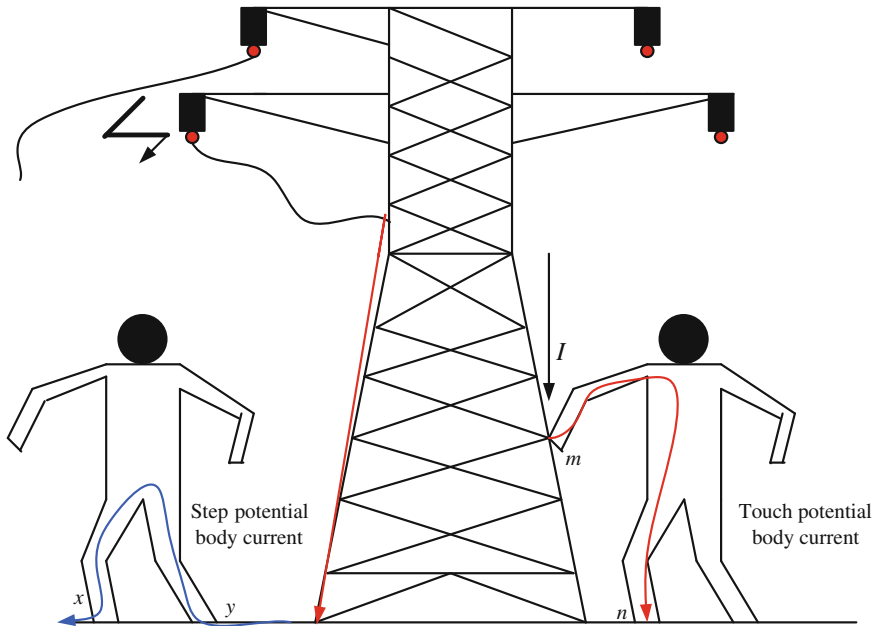


Fig. 6.12 Electric tower with peoples

in contact with it. In short, the touch potential is the voltage between the energized object and the feet of a person.

A current will flow through transmission tower to the ground if there is a fault in the transmission lines. As a result, the ground potential rise at the tower and the voltage gradient or electric field will appear based on the surrounding soil resistivity. This in turn will result in, a potential difference at the ground. The potential difference on the ground near the grounding system can be dangerous for the operator standing in the area of the grounding system. The potential difference between the two points on the earth surface separated by a distance of 1 m in the direction of the maximum voltage gradient is known as step potential.

The allowable body currents for 50 and 70 kg peoples are,

$$I_{b50\text{ kg}} = \frac{0.116}{\sqrt{t_s}} \tag{6.94}$$

$$I_{b70\text{ kg}} = \frac{0.156}{\sqrt{t_s}} \tag{6.95}$$

where t_s the time in seconds, a human body is gets in touch with a circuit at fault. The circuits for touch and step potentials are shown in Fig. 6.13. According to

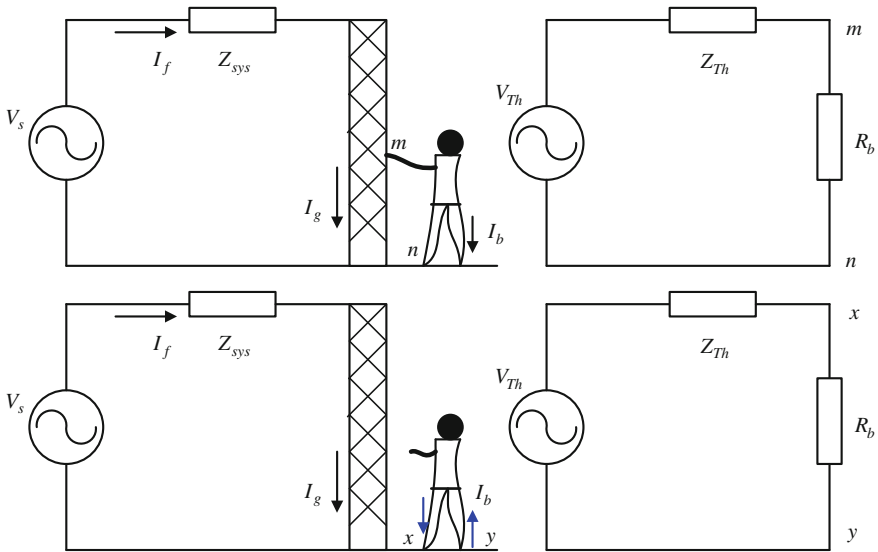


Fig. 6.13 Circuits for touch and step potentials

Laurent assumption [4], Thevenin impedances for touch and step voltage circuits are,

$$Z_{ThT} = \frac{R_f}{2} \tag{6.96}$$

$$Z_{ThS} = 2R_f \tag{6.97}$$

where R_f is the feet resistance of a person. However, the expression of feet resistance for human being is,

$$R_f = 3\rho \tag{6.98}$$

where ρ is the soil resistivity. Substituting Eq. (6.98) into Eqs. (6.96) and (6.97) yields,

$$Z_{ThT} = \frac{3\rho}{2} = 1.5\rho \tag{6.99}$$

$$Z_{ThS} = 2 \times 3\rho = 6\rho \tag{6.100}$$

The expressions of tolerable touch and step potentials are,

$$V_{touch} = I_b(R_b + 1.5 \rho) \quad (6.101)$$

$$V_{step} = I_b(R_b + 6 \rho) \quad (6.102)$$

where R_b is the human-body resistance. According to Thapar et al. [5], the ground resistance of a single foot is

$$R_f = \frac{\rho_s}{4r} C_s \quad (6.103)$$

$$C_s = 1 + \frac{16r}{\rho_s} \sum_{n=1}^{\infty} K^n R_m(2nh_s) \quad (6.104)$$

$$K = \frac{\rho - \rho_s}{\rho + \rho_s} \quad (6.105)$$

where

C_s is the surface layer derating factor,

K is the reflection factor,

ρ_s is the resistivity at the surface layer,

ρ is the resistivity at the layer below the distance h_s .

The surface layer derating factor C_s is expressed as [5],

$$C_s = 1 - \frac{0.09 \left(1 - \frac{\rho}{\rho_s}\right)}{2h_s + 0.09} \quad (6.106)$$

According to IEEE Standard [IEE 80-2000] [6], the touch and step potentials for the human body resistance (R_b) of 1000 Ω and different fault circuits as seen in Fig. 6.13 can be modified as,

$$V_{touch} = I_b \left(1000 + \frac{R_f}{2}\right) \quad (6.107)$$

$$V_{step} = I_b(1000 + 2R_f) \quad (6.108)$$

where I_b is the current through the human body. The touch potential limits for 50 and 70 kg body weights are,

$$V_{touch50\text{kg}} = (1000 + 1.5\rho C_s) \frac{0.116}{\sqrt{t_s}} \quad (6.109)$$

$$V_{touch70\text{kg}} = (1000 + 1.5\rho C_s) \frac{0.157}{\sqrt{t_s}} \quad (6.110)$$

The step potential limits for 50 and 70 kg body weights are,

$$V_{step50\text{kg}} = (1000 + 6\rho C_s) \frac{0.116}{\sqrt{t_s}} \quad (6.111)$$

$$V_{step70\text{kg}} = (1000 + 6\rho C_s) \frac{0.157}{\sqrt{t_s}} \quad (6.112)$$

Example 6.5 Alexander touches an energized tower for 0.3 s and his body weight is 70 kg. The resistivity at the surface layer and at a distance of 0.3 m inside the soil are found to be 70 and 50 Ω -m, respectively. Determine the surface layer derating factor, touch and step potential.

Solution

The surface layer derating factor can be determined as,

$$C_s = 1 - \frac{0.09 \left(1 - \frac{\rho}{\rho_s}\right)}{2h_s + 0.09} = 1 - \frac{0.09 \left(1 - \frac{50}{70}\right)}{2 \times 0.3 + 0.09} = 0.96$$

The value of the touch potential can be calculated as,

$$V_{touch70\text{kg}} = (1000 + 1.5\rho C_s) \frac{0.157}{\sqrt{t_s}} = (1000 + 1.5 \times 50 \times 0.96) \frac{0.157}{\sqrt{0.3}} = 307.28 \text{ V}$$

The value of the step potential is,

$$V_{step70\text{kg}} = (1000 + 6\rho C_s) \frac{0.157}{\sqrt{t_s}} = (1000 + 6 \times 50 \times 0.96) \frac{0.157}{\sqrt{0.3}} = 369.19 \text{ V}$$

Example 6.6 Robinson touches an energized tower for 0.5 s. The surface layer derating factor is found to be 0.75 for a soil resistivity 30 Ω -m at a distance 0.05 m inside the soil. Find the surface layer resistivity, touch and step potential if the body weight of the Robinson is 50 kg.

Solution

The surface layer soil resistivity can be determined as,

$$C_s = 1 - \frac{0.09 \left(1 - \frac{\rho}{\rho_s}\right)}{2h_s + 0.09}$$

$$0.75 = 1 - \frac{0.09 \left(1 - \frac{30}{\rho}\right)}{2 \times 0.05 + 0.09}$$

$$0.75 = 1 - 0.47 + \frac{14.21}{\rho}$$

$$\rho = \frac{14.21}{0.22} = 64.59 \Omega\text{-m}$$

The value of the touch potential can be calculated as,

$$V_{touch50\text{kg}} = (1000 + 1.5\rho C_s) \frac{0.116}{\sqrt{t_s}} = (1000 + 1.5 \times 64.59 \times 0.75) \frac{0.116}{\sqrt{0.5}}$$

$$= 175.97 \text{ V}$$

The value of the step potential is,

$$V_{step70\text{kg}} = (1000 + 6\rho C_s) \frac{0.116}{\sqrt{t_s}} = (1000 + 6 \times 64.59 \times 0.75) \frac{0.116}{\sqrt{0.5}} = 211.73 \text{ V}$$

Practice problem 6.5

Luis Beltran touches an energized distribution pole for 0.3 s and his body weight is found to be 50 kg. The resistivity at the surface layer and at a distance of 0.02 m inside the soil are found to be 60 and 25 $\Omega\text{-m}$, respectively. Calculate the surface layer derating factor, touch and step potential.

Practice problem 6.5

A 70 kg person touches an energized tower for 0.5 s. The surface layer derating factor is found to be 0.8 for a soil resistivity 35 $\Omega\text{-m}$ at a distance of 0.04 m inside the soil. Determine the surface layer resistivity, touch and step potential.

Exercise Problems

- 6.1 The Wenner four poles equal method is used to measure the soil resistivity measurement near a power station. The five readings of soil resistance were recorded at a probe distance of 1, 2, 3, 4 and 5 m using Fluke 1625 earth tester equipment. The corresponding values of the soil resistance were 35, 18, 13,

- 11.2, 10.2 and 13 Ω , respectively. Determine the soil resistivity and plot it with respect to the probe distance.
- 6.2. A 66/11 kV substation has been installed near an industrial area. The measurement of the soil resistance are recorded at a probe distance of 1, 2, 3, 4 and 5 m using the F. Wenner four poles equal method. The corresponding values of the soil resistance were 12.4, 4.29, 3.95, 1.26 and 0.86 Ω , respectively. Determine the average soil resistivity in that substation.
- 6.3 The Lee's portioning method is used to measure the soil resistivity of an 11/66 kV substation of a country. The resistances of 4.3 and 4.21 Ω are measured between the probes 2 and 3, probes 3 and 4, respectively. Calculate the soil resistivity if the probe separation distance 1.5 m in both cases.
- 6.4 The Schlumberger unequal method is used to measure the soil resistivity of a substation. The value of the resistance of the soil is found to be 10.5 Ω by setting a distance of 1.5 m between the current and the potential probes. Calculate the soil resistivity if the two potential probes separation distance is 4 m.
- 6.5 The resistance of the soil is measured using the Schlumberger unequal method and the value is found to be 10 Ω . In this measurement, the distance between the current probe and the potential probe is set to be 1 m. Find the soil resistivity if the distance between the two potential probes is 3 m.
- 6.6 A person touches an energized distribution pole for 0.2 s, and his body weight 70 kg. The resistivity at the surface layer and at a distance of 0.02 m inside the soil are found to be 30 and 12 Ω -m, respectively. Find the surface layer derating factor, touch and step potential.

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