Chapter 5
Earth Electrode Resistance

5.1 Introduction

In general resistivity methods can be applied for studying variations of resistivity with depth (depth sounding methods) or for studying lateral changes in resistivity (horizontal profiling methods) as long as the units have a resistivity contrast. Often this is connected to rock porosity and fraction of water saturation of the pore spaces.

The electrical resistivity method is one of the most useful techniques in groundwater hydrology exploration because the resistivity of a rock is very sensitive to its water content. In turn, the resistivity of water is very sensitive to its ionic content. Other applications include studies on Water table depth, Groundwater quality, Aquifer exploration, mineral Exploration, Detection of cavities, Waste site exploration and General stratigraphic mapping.

In the context of Electrical Engineering Soil Resistivity studies have become utmost important in the design of Earthing or Grounding Systems. This chapter discusses about the practical considerations on Earthing and the impact of a Multi layer soil on the Earth Electrode Resistance.

5.2 Requirements of an Earthing System

Earthing or Grounding may be described as a system of electrical connections to the general mass of earth. This system of electrical connections consists of components of an electrical system and metal works associated with equipment, apparatus and appliances. Earth is a conductor covered with the resistive material, soil. The purpose of grounding is to provide direct path for the fault currents to the soil while maintaining the step and touch voltages at acceptable values, i.e. for limiting potential with respect to the general mass of earth in order to ensure safety.

A good grounding system is important for the protection of an overall system facility. From a good earthing system we anticipate on Protection of buildings and installations against lightning. Safety of human and animal life by limiting touch and step voltages to safe values. Electromagnetic compatibility (EMC) i.e. limitation of electromagnetic
disturbances and correct operation of the electricity supply network and to ensure good power quality.

All these functions are provided by a single earthing system that has to be designed to fulfill all the requirements. Some elements of an earthing system may be provided to fulfill a specific purpose, but are nevertheless part of one single earthing system. Standards require all earthing measures within an installation to be bonded together, forming one system. A complete grounding system might include only one earth electrode, an entire group of electrodes with a grounding grid, or anything in between and beyond.

There are many factors that determine how well a grounding system performs. Two major parameters are its resistance to remote earth and the resistivity of the local soil. Each of these values can be measured to help determine and design the best solution for the grounding system. The resistance to remote earth of the grounding system needs to be at a minimum in order to sustain its effectiveness. A few of the components that make up this resistance are the physical properties of the material used to make the electrode and conductor, all connections made, contact resistance between the electrode and the soil, and the soil resistivity.

In many of the applications of grounding, low earth resistance is essential to meet electrical safety standards. The intention of keeping the earth resistance low is to provide a path back to the supply of sufficiently low impedance to permit the protective devices to operate properly. The resistance figures also vary from industry to industry. Accepted industry standards stipulate that transmission substations should be designed not to exceed 1 \( \Omega \). In distribution substations, the maximum recommended resistance is for 5 \( \Omega \) or even 1 \( \Omega \). In most cases, the buried grid system of any substation will provide the desired resistance. In light industrial or in telecommunication central offices, 5 \( \Omega \) is often the accepted value. For lightning protection, the arrestors should be coupled with a maximum ground resistance of 1 \( \Omega \).

5.3 Electrical properties of the earthing system

The electrical properties of earthing system depend essentially on two parameters: Earthing resistance and configuration of the earth electrode. Earthing resistance determines the relation between earth voltage and the earth current value. The
configuration of the earth electrode determines the potential distribution on the earth surface, which occurs as a result of current flow in the earth. The potential distribution on the earth surface is an important consideration in assessing the degree of protection against electric shock because it determines the touch and step potentials.

### 5.3.1 Earthing resistance

This has two components: the Dissipation Resistance $R_d$, which is the resistance of the earth between the earth electrode and the reference earth and resistance $R_l$ of the metal parts of the earth electrode and of the earthing conductor. The resistance $R_l$ is usually much smaller than the dissipation resistance $R_d$. Thus, usually the earthing resistance is estimated to be equal to the dissipation resistance $R_d$.

Also in AC circuits one must consider essentially the impedance of an earthing $Z_1$, which is the impedance between the earthing system and the reference earth at a given operating frequency. The reactance of the earthing system is the reactance of the earthing conductor and of metal parts of the earth electrode. At low frequencies such as the 50Hz supply frequency and associated harmonics, reactance is usually negligible in comparison to earthing resistance, but must be taken into account for high frequencies such as lightning transients. Thus, for low frequencies, it is assumed that the earthing impedance $Z_1$ is equal the dissipation resistance $R_d$, which is in turn assumed to be approximately equal to the earthing resistance, $R$.

$$Z_1 \approx R_d \approx R$$

The earthing resistance $R$ of an earth electrode depends on the earth resistivity $\rho$ as well as the electrode geometry.

### 5.3.2 Electrode configuration

In order to achieve low values of Earth Resistance the current density flowing from the electrode metal to earth should be low, i.e. the volume of earth through which the current flows is as large as possible. Once the current flows from metal to earth it spreads out, reducing current density. If the electrode is physically small, e.g. a point, this effect is large, but is very much reduced for a plate where spreading is only
effective at the edges. This means that rod, pipe, or wire electrodes have a much lower dissipation resistance than, for example, a plate electrode with the same surface area. Moreover, it is well documented in literature that DC and AC induced corrosion increases with current density. Low current density extends electrode life.

### 5.3.2.1 Hemisphere type electrode

![Figure 5.1 - Hemispherical Electrode - Cross Sectional elevation](image)

The current entering into the electrode will flow radially and the potentials will gradually decrease as it goes outwards from the surface of the electrode. Now if we consider a hemispherical element of thickness $dx$ at a distance $x$, the resistance of the elemental hemisphere $dR$ is,

$$dR = \frac{\rho dx}{2\pi x^2} \quad (5.2)$$

Where,

- $\rho$ - Resistivity of the homogeneous soil

Total electrode resistance is the resistance between the point of entry of current and the general mass of the earth. To obtain this integrate from the electrode surface to infinity,

$$R = \int \frac{\rho dx}{2\pi x^2}$$

$$R = \frac{\rho}{2\pi r} \quad (5.3)$$
Consider a circular plate electrode of radius $r$, lying on the surface of the earth of homogeneous resistivity $\rho$. Making the assumptions that all currents coming out from below the plate are vertical and all current coming out from the edges go out radially from the edge, the resistance of an elemental area of thickness $dx$ at distance $x$ is given by:

$$dR = \frac{\rho \, dx}{\pi (\pi x + 2x^2 + r^2)} \tag{5.4}$$

Thus to obtain the total Electrode Resistance,

$$R = \int \frac{\rho}{2\pi r} \left[ \frac{1.4628}{x + 0.4436r} - \frac{1.4628}{x + 1.1272r} \right] \, dx$$

$$= \left. \frac{\rho}{4.295r} \ln \frac{x + 0.4436r}{x + 1.1272r} \right|_0^r = \frac{\rho}{4.295r} \ln \frac{1.1272}{0.4436}$$

$$= \frac{\rho}{4.6r} \tag{5.5}$$

Let's consider the area of the plate to be $A$. Now $A = \pi r^2$,

$$r = \sqrt{\frac{A}{\pi}} \tag{5.6}$$

Therefore substituting (5.6) in (5.5),
Since approximations are used in the calculation, it would have yielded a higher value than the answer from equation (5.7). So, the following equation is conveniently used as the Electrode Resistance of a circular plate.

\[ R = \frac{\rho}{4.6 \sqrt{A}} \]  

(5.7)

5.3.2.3 Rod/pipe type electrode

Let's consider a rod electrode of radius \( r \) and length \( l \). Let's assume that the current flow outwards from the vertical section is horizontal and from the lower hemispherical end is radial outwards. Consider an elemental area at distance \( x \), now the resistance of the elemental area is,
\[ dR = \frac{\rho dx}{2\pi l + 2\pi r^2} \]  

(5.9)

Total resistance of the Rod Electrode is,

\[ R = \int \frac{\rho}{2\pi l} \left( \frac{1}{x(x+l)} \right) dx \]

\[ = \left[ \frac{\rho}{2\pi l} \ln \left( \frac{x}{x+l} \right) \right] \]

\[ R = \frac{\rho l}{2\pi l} \ln \frac{r+l}{r} \]

(5.10)

Generally \( l >> r \) so,

\[ R = \frac{\rho l}{2\pi l} \ln \frac{l}{r} \]

(5.11)

The above equation (5.11) for the Resistance of a Rod Electrode is given in BS7430 as follows.

\[ R = \frac{\rho l}{2\pi l} \left[ \ln \left( \frac{8L}{d} \right) - 1 \right] \]

(5.12)

Where,

- \( L \) - Buried Length of the Electrode in \( m \)
- \( d \) - Diameter of the Electrode in \( m \)

The earth resistance depends significantly on how deep the electrode is sunk in the ground. This is because the moisture content is higher and more stable for deeper ground layers than for shallow layers. Layers near the surface are influenced more by seasonal and short-term weather variations and are subject to freezing.

The most versatile type of earth electrode is the driven rod. On sites where soil resistivity is high, the use of deep driven rods to lower the resistance is one option.

Figure 5.4 shows for a rod earth electrode how the earthing resistance reduces considerably as the depth of a rod electrode increases. However, it is not always possible to place electrodes at the preferred depth for geological reasons, for example.
where there are rocks or obstructions close to the surface or where the electrode system covers a large area.

![Graph showing Electrode Resistance Vs Buried Length](figure5.4)

<table>
<thead>
<tr>
<th>Buried Length (L)</th>
<th>Electrode Resistance (Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>25</td>
<td>60</td>
</tr>
<tr>
<td>30</td>
<td>70</td>
</tr>
</tbody>
</table>

Equation (5.11)  
Equation (5.12)

Figure 5.4 - Dissipation Resistance of a Rod Electrode as a function of its buried length ($\rho = 1000 \Omega m$ and $r = 25 mm$)  
*Original is in color*

The advantage of these is that they pass through soil layers of different conductivity and are particularly useful in places where the shallow layers have poor conductivity. In this way it is easy to obtain an expected electrode resistance as seen in Figure 5.4. Another advantage of rod electrodes is that they can be installed in places where there is a limited surface area available to install the electrode. However, surface potential distribution of rod electrodes is unfavorable, so in practice a combination of rod and surface earth electrodes are also used, in order to obtain both a good resistance and desirable surface potential distribution.

5.3.2.3.1 Effective Resistance Area of a Rod electrode

The current flowing from the earth electrode goes through layers of soil immediately surrounding the electrode. Also the cross sectional area $s$ of the soil layers nearest to the electrode is rather small and the soil is relatively a poor conductor of electricity.
Therefore, the effective resistance of the conductor is concentrated mainly in the first few meters of soil immediately surrounding the electrode. This fact can be illustrated as follows.

Using equation (5.11) the resistance \( R \) of the electrode up to a distance \( x \) from the electrode is,

\[
R_x = \frac{\rho}{2\pi l} \ln \left( \frac{x}{x + l} \right)
\]

Now let's consider a numeric example where \( l = 2.5\ m \) and \( r = 25\ mm \) and soil resistivity \( \rho = 100\ \Omega\cdot m \). Substituting in equation (5.11) the total resistance of the electrode is.

\[
R = \frac{100}{2\pi \times 2.5} \ln \left( \frac{2.5}{0.025} \right) = 29.3174\ \Omega
\]

Using equation (5.14),

\[
R_x = \frac{100}{2\pi \times 2.5} \ln \left( \frac{x(2.525)}{0.025(x + 2.5)} \right)
\]

\[
R = 29.3808 - 6.3662 \ln \left( \frac{x + 2.5}{x} \right)
\]

The resulting plot of \( R_x \) vs. \( x \) is shown in Figure 5.5. From Figure 5.5 it can be observed that 50\% of the resistance is from just 0.28m, 75\% in 1.14m, 90\% in 4.15m, 95\% in 9.21m and 99\% in 43.4m. Increase in resistance is very slow after 90\% value. Thus in general it is considered that the resistance of a rod electrode has a resistance area having a radius of approximately twice the length, i.e. for this particular example it is 5m's where the value is 91.4\%. This is the reason why when an electrode is planted it should not be closer than 2 or 3 times its length from other major earths. The area within this distance of the rod is the so-called effective resistance area.
Distance from Electrode, $x$ vs Resistance at distance $x$

- $X: 4.152$
- $Y: 26.38$
- $X: 1.139$
- $Y: 21.98$
- $X: 0.278$
- $Y: 14.67$

Figure 5.5 - Variation of Earth Resistance at distance, $x$, from the electrode

5.3.2.4 Slip or conductor type

Trench Electrodes, conductors buried horizontally under the surface of the ground, also make very good connections to earth. They are particularly effective when...
down-conductor is connected to a point in the middle of the trench electrode. These horizontal electrodes have special advantage where high resistivity soil has a shallow layer of low resistivity soil above it. The Strip Electrode is similar to a rod electrode of circular cross section buried horizontally such that a hemispherical cross section is below the soil (Figure 5.6).

Lets consider an elemental half cylinder with half hemispherical ends, at a distance \( x \), below and thickness \( dx \). Now the resistance of the elemental considered is,

\[
dR = \frac{\rho \, dx}{\pi \left( \frac{x}{2} + \frac{1}{2} \right)}
\]

The total circular conductor Electrode Resistance is,

\[
R = \frac{\rho}{\pi} \int \frac{dx}{\frac{x}{2} + \frac{1}{2}}
\]

\[
= \frac{\rho}{\pi l} \left[ \ln \frac{x}{x + l} + \frac{1}{2} \right] dx
\]

\[
= \frac{\rho}{\pi l} \left[ \ln \frac{x}{x + l} + \frac{1}{2} \right]
\]

\[
R = \frac{\rho}{\pi l} \ln \left( \frac{l + 2r}{2r} \right)
\]

(5.16)

When \( l \gg r \),

\[
R = \frac{\rho}{\pi l} \ln \frac{l}{2r}
\]

(5.17)

When the circular conductor of radius \( r \) is replaced by a strip of width \( \mu \), this becomes,

\[
R = \frac{\rho}{\pi l} \ln \frac{l}{\mu}
\]

(5.18)

If the tape is buried at a depth \( t \), instead at surface,

\[
R = \frac{\rho}{2\pi l} \ln \frac{2t}{\mu t}
\]

(5.19)
5.3.2.5 Meshed electrodes

Another example of the use of conductors buried under the surface of the earth is the ground-grid mesh. These are constructed as a grid placed horizontally at shallow depth cable with exposed metal sheath or armour which behaves similarly to a strip-type earth electrode. Grid meshes are often used to complement rods or can be used separately when deep driven rods are impractical due to soil and terrain considerations.

Grid meshes are often used for the earthing in substations to create an equipotential platform and also to handle the high fault currents returning to the transformer neutrals. They are particularly useful when multiple injection points are required, at a substation for example. In this case a number of items will be connected to the grid at various locations; the mesh provides a good earth irrespective of the injection point of the fault current. Earthing resistance of buried grid meshes can be considerably lower than those implemented using vertical earth spikes. Increasing the area of the grid coverage can also significantly reduce the earth resistance.

5.3.2.6 Foundation earth electrodes

These are formed from conductive structural parts embedded in concrete foundation providing a large area contact with the earth.

5.4 Electrical properties of the ground

The calculation of the earthing resistance requires a good knowledge of the soil properties. The electrical properties of the ground are characterized by the earth resistivity \( \rho \). Therefore the soil stratum is required to be analyzed to determine the soil Resistivity, at the design stage.

Soil resistivity has a direct effect on the resistance of the grounding system. The evaluation of the resistivity of the local soil can determine the best location, depth, and size of the electrodes in a grounding system, and can also be used for many other applications. As discussed in earlier chapters geological survey uses the soil resistivity to locate ore, clay, gravel, etc. beneath the earth’s surface. Depth and thickness of bedrock can also be determined. The degree of corrosion of the local soil also can be
obtained from its resistivity value. Due to these many reasons, it is necessary to measure the resistivity of the local soil.

A large variation in the value of $\rho$ is a problem. In many practical situations, a homogenous ground structure will be assumed with an average value of $\rho$, which must be estimated on the basis of soil analysis or by measurement. The determination of $\rho$ is often a complicated task for the ground does not have a homogenous structure, but is formed of layers of different materials and the resistivity of a given type of ground varies widely (Table 5.1) and is very dependent on moisture content.

Where no information is available about the value of $\rho$ it is usually assumed $\rho = 100\Omega m$. However, as Table 5.1 indicates, the real value can be very different; one important point is that the current distribution in the soil layers used during measurement should simulate that for the final installation. Consequently, measurements must always be interpreted carefully. So acceptance testing of the final installation, together with an assessment of likely variations due to weather conditions and over lifetime, must be undertaken.

### 5.4.1 The Approximate resistivity values of common rock types

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity ($\Omega m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>$\infty$</td>
</tr>
<tr>
<td>Pyrite</td>
<td>0.3</td>
</tr>
<tr>
<td>Galena</td>
<td>0.002</td>
</tr>
<tr>
<td>Quartz</td>
<td>$4\times10^3 - 2\times10^4$</td>
</tr>
<tr>
<td>Calcite</td>
<td>$1\times10^5 - 1\times10^{13}$</td>
</tr>
<tr>
<td>Rock Salt</td>
<td>$30 - 1\times10^3$</td>
</tr>
<tr>
<td>Mica</td>
<td>$9\times10^2 - 1\times10^{11}$</td>
</tr>
<tr>
<td>Granite</td>
<td>$100 - 1\times10^6$</td>
</tr>
<tr>
<td>Gabbro</td>
<td>$1\times10^5 - 1\times10^9$</td>
</tr>
<tr>
<td>Basalt</td>
<td>$10 - 1\times10^7$</td>
</tr>
<tr>
<td>Limestones</td>
<td>$50 - 1\times10^7$</td>
</tr>
<tr>
<td>Sandstones</td>
<td>$1 - 1\times10^6$</td>
</tr>
<tr>
<td>Dolomite</td>
<td>$100 - 10000$</td>
</tr>
<tr>
<td>Sand</td>
<td>1 - 1000</td>
</tr>
<tr>
<td>Clay</td>
<td>1 - 100</td>
</tr>
<tr>
<td>Ground Water</td>
<td>0.5 - 300</td>
</tr>
<tr>
<td>Sea Water</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 5.1 - Resistivities of Some materials
Although some native metals and graphite conduct electricity, most rock-forming minerals are electrical insulators. Measured resistivities in Earth materials are primarily controlled by the movement of charged ions in pore fluids. Although water itself is not a good conductor of electricity, ground water generally contains dissolved compounds that greatly enhance its ability to conduct electricity. Hence, porosity and fluid saturation tend to dominate electrical resistivity measurements. In addition to pores, fractures within crystalline rock can lead to low resistivities if they are filled with fluids.

5.4.2 Principle factors effecting soil resistivity

5.4.2.1 Type of Soil

The soil composition can be clay, gravel, loam, rock, sand, shale, silt, stones, etc. In many locations, soil can be quite homogenous, while other locations may be mixtures of these soil types in varying proportions. As discussed in earlier chapters very often, the soil composition is in layers or strata.
5.4.2.2 Climate

Obviously, arid and good rainfall climates are at opposite extremes for conditions of soil resistivity.

5.4.2.3 Seasonal Conditions

The effects of heat, moisture, drought and frost can introduce wide variations in "normal" soil resistivity. Soil resistivity increases few percent with moisture content while soil temperatures below freezing greatly increase soil resistivity.

The moisture content can change over a wide range, depending on geographical location and weather conditions, from a low percentage for desert regions up to about 80% for swampy regions. Moisture content can be a significant factor in determining the resistivity of the local soil. Figure 5.8 shows the influence of the moisture content on the resistivity value. The drier the soil, the higher the resistivity. The soil resistivity remains relatively low (and constant) if the moisture content of the soil is greater than 15% (by weight,) and skyrockets for lower values of moisture content.

Also the effect of freezing is similar to that of drying, the resistivity increases significantly at higher freezing levels.

It should be noted that however the moisture alone is not the predominant factor in the low resistivity soils. If the water is relatively pure, it will be high resistivity unless the soil contain sufficient natural element to form a conducting electrolyte, the abundance
of water will not provide the soil with adequate conductivity. The value of high moisture content is advantageous in increasing the solubility of existing natural elements in the soil, and in providing for the solubility of ingredients which may be artificially introduced to improve the soil conductivity.

Figure 5.9 shows the influence of varying temperature on the soil resistivity value. The temperature coefficient of resistivity for soil is negative, but is negligible for temperature above freezing point. At about 20°C, the resistivity change is about 9% per 1°C. With temperature, the colder the soil is, the higher the resistivity. Due to seasonal changes where the temperature can change drastically for a particular area, the resistivity of the local soil can also change drastically.

5.4.2.4 Other Factors

Grain size and distribution, and closeness of packing are also contributory factors since they have much to do with retention of soil moisture, as well as providing good conditions for a closely packed soil in good contact with the earth rod.

Another significant factor in the determination of soil resistivity is the content of minerals, such as salts or other chemicals dissolved in the contained water. For values of 1% (by weight) salt content, the soil resistivity remains low (and constant,) and skyrockets for lower values of salt content.
Many of these factors (moisture content, mineral content, compactness, and temperature,) of the local soil can change during the life of the grounding system, and therefore change the resistance to remote earth of that grounding system. For these reasons the calculations of earth resistance and the planning of electrodes can be performed up to a limited level of accuracy.

5.5 Surface potential distribution

Earthing voltage, as well as distribution of the earth surface potential during the current flow in the earthing system, is important parameters for protection against electric shock. Earthing voltage ($V_e$), is equal to the earthing potential (assuming that the potential of the reference earth is equal zero). Using equation (5.10), the earthing potential can be described as follows,

$$V_e = I_e R_e = \frac{\rho I_e}{2 \pi l} \ln \frac{r + l}{r}$$

Where,

$I_e$ - Earth Current

Under fault conditions, the earth electrode is raised to a potential with respect to the general mass of earth. This results in the existence of voltages in the soil around the electrode that may be injurious to telephone and pilot cables, whose cores are substantially at earth potential, owing to the voltage to which the sheath of such cables are raised. This happens mainly in connection with large electrode systems as at power stations and sub stations.

The voltage gradient at the surface of ground may also constitute a danger to life, specially where the cattle are concerned. This occurs principally with pole mounted sub stations with low voltage systems.

5.5.1 Surface Potential Distribution due to a Rod Electrode buried in a homogeneous medium

The potential of any point located at distance $x$ from the middle of earthing electrode, in which earthing current $I_e$ flows, can be formulated with the following equation using starting with the equation (2.13) and equation (2.14).
Since it is assumed that the current flows outwards from the vertical section is horizontal and from the lower hemispherical end is radial outwards the total current \( I_c \) crossing a cylindrical plus hemispherical surface is given by,

\[
I_c = (2\pi x + 2\pi x') J
\]  

(5.21)

Thus from (2.14),

\[
\frac{A}{x} = \rho x = \frac{I_c \rho}{2\pi x (l + x)} = \frac{J \rho}{2\pi l (l + x)}
\]  

(5.22)

Therefore,

\[
A = \frac{\rho l x}{2\pi (l + x)}
\]  

(5.23)

Hence from (2.13),

\[
V_c = \frac{\rho l x}{2\pi (x + l)}
\]  

(5.24)

Which is the voltage at a distance \( x \) due to current flowing in the center of a rod electrode buried to a distance \( l \) from the surface.

Following is an illustration of the surface potential distribution due to a current flowing in a rod type electrode. Figure 5.10 shows a rod type electrode embedded in a homogeneous ground.

With Figure 5.10 it is possible for us to calculate the step and touch potentials due to certain earth fault condition to evaluate the degree of expected shock at a specified distance from the electrode. Step and touch voltage situations arise when it is possible for a person to make simultaneous contact with a part of an electrical system which is not live under normal conditions but has become live due to the passage of a fault current, and another conductive part which is at a different potential. This situation is described as ‘indirect contact’ with live parts.
Figure 5.10 - Notational representation of Surface Potential distribution of a rod electrode buried in a homogeneous medium.

\( l = 2.5m, r = 25mm, \rho = 100\Omega m, I_e = 100A \)

A common step and touch voltage situation arises in and around substations under earth fault conditions wherein the earth fault current flows through the earth electrode and grid system, and it is possible for a person to make simultaneous contact with two parts which are at a different potential due the passage of the earth fault current.

5.5.2 Touch Potential

Touch potential is the voltage between the energized object and the feet of a person in contact with the object, i.e. the voltage between a palm and a foot of a person who is just touching the earth electrode or metal parts connected to it (Figure 5.10). It is equal to the difference in voltage between the object (which is at a distance of 0m's) and a point 1m distance away. It should be noted that 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 in contact with it.

5.5.3 Step Potential

Step potential is the voltage between the feet of a person standing near an energized grounded object. It is equal to the difference in voltage, given by the voltage distribution curve, between two points at 1 m distances from the "electrode" (Figure 5.10). A person could be at risk of injury during a fault simply by standing near the grounding point.

5.6 Methods of Earth Electrode Resistance Measurements of a single Electrode

When an electrode system has been designed and installed, it is usually necessary to measure and confirm the earth resistance between the electrode and reference earth. Grounding systems should be tested upon installation and then annually during their service life. The initial testing establishes a performance baseline, confirms that the design specification is met and validates the quality of the installation. Annual testing ensures the continued integrity of the system and provides protection against degradation prior to equipment damage or performance problems.

The most commonly used method of measuring the earth resistance of an earth electrode is the 3-point measuring technique. Other more complex methods, such as the Slope Method or the Four Pole Method, have been developed to overcome specific problems associated with this simpler procedure, mainly for measurements of the resistance of large earthing systems or at sites where space for locating the test electrodes is restricted.

Regardless of the measurement method employed, it should be remembered that the measurement of earth resistance is as much an art as it is a science, and resistance measurements can be affected by many parameters, some of which may be difficult to quantify. As such, it is best to take a number of separate readings and average them, rather than rely on the results of a single measurement.

5.6.1 Fall of Potential Method

The 3-point method or the Fall of Potential method is the most recognized method for measuring the resistance to earth of a grounding system, and is best suited to small
systems that don't cover a wide area. It is simple to carry out and requires a minimal amount of calculation to obtain a result. This method is generally not suited to large earthing installations, as the stake separations needed to ensure an accurate measurement can be excessive, requiring the use of very long test leads.

This method comprises the Earth Electrode to be measured and two other electrically independent test electrodes, usually labeled \( P \) (Potential) and \( C \) (Current) (Figure 5.11). An alternating current \( (I) \) is passed through the outer electrode \( C \) and the voltage is measured, by means of an inner electrode \( P \), at some intermediary point between them. The Earth Resistance is simply calculated using Ohm's Law:

\[
R_e = \frac{V}{I}.
\]

![Figure 5.11 - 3-Point Method of Earth Resistance Measurement](image)

When performing a measurement, the aim is to position the auxiliary test electrode \( C \) far enough away from the earth electrode under test so that the auxiliary test electrode \( P \) will lie outside the effective resistance areas of both the earth system and the other
test electrode (Figure 5.11). If the current test electrode is too close, the resistance areas will overlap and there will be a steep variation in the measured resistance as the voltage test electrode is moved (Figure 5.12(b)). If the current test electrode is correctly positioned, there will be a 'flat' (or very nearly so) resistance area somewhere in between it and the earth electrode (Figure 5.12(a)).

The Fall of Potential method incorporates a check to ensure that the test electrodes are indeed positioned far enough away for a correct reading to be obtained. It is advisable that this check be carried, as it is really the only way of ensuring a correct result. To perform a check on the resistance figure, two additional measurements should be made; the first with the voltage test electrode (P) moved 10% of the original voltage electrode-to-earth system separation away from its initial position, and the second
with it moved a distance of 10% closer than its original position, as shown in Figure 5.11.

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

5.6.2 The 62% Method

The Fall of Potential method can be adapted slightly for use with medium sized earthing systems. Based on empirical data the ohmic value measured at 62% of the distance from the ground-under-test to the remote current probe, is taken as the system ground resistance. Therefore this adaptation is often referred to as the 62% Method, as it involves positioning the inner test stake at 62% of the earth electrode-to-outer stake separation (recall that in the Fall-of-Potential method, this figure was 50%).

All the other requirements of test stake location - that they be in a straight line and be positioned away from other structures - remain valid. When using this method, it is also advisable to repeat the measurements with the inner test stake moved ±10% of the earth electrode-inner test stake separation distance, as before.

The main disadvantage with this method is that the theory on which it is based relies on the assumption that the underlying soil is homogeneous, which in practice is rarely the case. Thus, care should be taken in its use and a soil resistivity survey should always be carried out. Alternatively, one of the other methods should be employed.

5.6.3 Other Test Methods

Many other methods exist for taking earth resistance measurements. Many of these methods have been designed in an attempt to alleviate the necessity for excessive
electrode separations, when measuring large earth systems, or the requirement of having to know the electrical centre of the system.

5.6.3.1 The Slope Method

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

The additional measurement and calculation effort tends to relegate this system to use with only very large or complex earthing systems.

5.6.3.2 The Star-Delta Method

This technique is well suited to use with large systems in built up areas or on rocky terrain, where it may be difficult to find suitable locations for the test electrodes, particularly over long distances in a straight line.

Three test electrodes, set up at the corners of an equilateral triangle with the earth system in the middle, are used and measurements are made of the total resistance between adjacent electrodes, and also between each electrode and the earthing system.

Using these results, a number of calculations are performed and a result can be obtained for the resistance of the earth system.

5.6.3.3 The Four Potential Method

This technique helps overcome some of the problems associated with the requirement for knowing electrical centre of the earthing systems being tested. The main drawback with the Four Potential method is that, like with the Fall of Potential method, it can require excessive electrode separation distances if the earthing system being measured is large.
This method is similar in set up to the standard Fall of Potential method and measurements are made with the voltage electrode at different positions and a set of equations are used to calculate the theoretical resistance of the system.

5.7 Limitations on calculating the Electrode Resistance

The calculation of earthing resistance is usually performed under the assumptions that the ground is boundless and of uniform structure with a given value of resistivity. It is possible to determine exact equations for earthing resistance but, in practice, their usefulness is very limited, especially in the case of complex and meshed earth electrodes where the mathematical relations become very complicated.

Furthermore, even a small inaccuracy in the value of the resistivity has a significant influence on the actual earthing resistance of meshed earth electrodes and it is often very difficult to determine the earth resistivity with the accuracy required. Because of this, the theoretical equations of earthing resistance derived in sections 5.3.2.1 - 5.3.2.4 usually used only for homogeneous earth structure. When it comes to the actual sub soil with a layered structure the Earth Resistance and the surface potential distribution will be effected due to the changes in current flow in the non-homogeneous media. Therefore it is essential to study the resistance of a rod electrode buried in a multi layer media since ultimately it can be more accurately estimated the depth of boring or the length of a rod electrode in a multi layer situation.

5.7.1 Surface Potential Distribution due to a Rod Electrodes buried in a Multi Layer Media.

Figure 5.13 shows a rod electrode driven in a multi layer earth. \( I_1, I_2, ..., I_n \) are considered to be current sources in the respective layers, due to current \( I \) entering into the electrode.

The work presented in paper [37] gives theoretical formulas for calculating the electrode resistance and surface potential distribution. In order to present the equations here, I start with the potential at the earth surface due to individual current sources in the layered structure.

The potential \( V_1 \) due to current source, \( I_1 \) in the 1st Layer,
Figure 5.13 - Driven rod in multi layer earth

And the general equation of the potential \( V \), due to current source, \( I_n \) in the \( N^{th} \) Layer is given as,

\[
V_n = \frac{\rho_n l}{2\pi} \int_{0}^{\pi} \frac{e^{-ikz} \sum (1 - k_1)(1 - k_2) \cdots (1 - k_{n-1})}{\alpha_{n-1} - \beta_{n-1} e^{2\pi i k} / \alpha_{n}} J_0(\lambda x) d\lambda
\]  

(5.25)

Where,

\[
\alpha_{n-1} = \alpha_{n-1} + \beta_{n-2} e^{2\pi i k} \rho
\]

\[
\alpha_{n} = \alpha_{n} + \beta_{n} e^{2\pi i k} \rho
\]

\[
\vdots
\]

\[
\beta_{n-1} = k(\alpha_{n-1} + \beta_{n-2} e^{2\pi i k})
\]

\[
\beta_{n} = k(\alpha_{n} + \beta_{n-1} e^{2\pi i k})
\]
Accordingly, the surface potential \( V_s(x) \) at distance \( x \) from the center of the electrode, due to a deep driven rod in an N-layer earth structure is given as,

\[
V_s(x) = \int_0^h V_i \, dt + \int_0^{h_2} V_i \, dt + \cdots + \int_0^{h_N} V_i \, dt
\]  
(5.27)

\[
= \frac{\rho l}{2\pi} \sum_{n=1}^{N} \left[ \prod_{i=1}^{n-1} (1-k_i) \right] \int_0^{h_n} \left[ \frac{\alpha_n e^{-\alpha x} + \beta_n e^{-\beta x}}{\alpha_n - \beta_n e^{-\gamma x}} \right] J_0(\lambda x) \, d\lambda \, dt
\]  
(5.28)

Where,

\[
h_i = \sum_{i=1}^N h_i \quad H_0 = 0 \quad H_N = l
\]

\[a_{n+1} = \frac{1}{\beta_n} \quad \beta_{n+1} = 0
\]

When it come to calculations the current \( I \) should be determined. For that it is assumed that the current density is inversely proportional to the resistivity, \( \rho \) so that it can be considered that the current in each layer is uniform. Thus,

\[
\rho_1 l_1 = \rho_2 l_2 = \cdots = \rho_N l_N
\]  
(5.29)

\[
I h_1 + I h_2 + \cdots + I(h_1 - h_2 - h_3 - \cdots) = I
\]  
(5.30)

Solving the above equations,

\[
\rho l = \sum_{n=1}^N \frac{l}{h_n + l - H_{n+1}}
\]  
(5.31)

Where,

\[
H_{n+1} = \sum_{i=1}^n h_i
\]

\( I \) - Current Flowing in the rod electrode

\( \rho_n \) - Resistivity of layer \( n \)

Finally the general equation to calculate surface potential \( V_s(x) \) at distance \( x \) from the center of the electrode, due to a deep driven rod in a N-layer earth structure is given as,

\[
V_s(x) = \frac{1}{2\pi} \sum_{i=1}^{N-1} \frac{l}{\rho_i} \sum_{n=1}^{i} \left[ \prod_{i=1}^{n-1} (1-k_i) \right] \int_0^{h_n} \left[ \frac{\alpha_n e^{-\alpha x} + \beta_n e^{-\beta x}}{\alpha_n - \beta_n e^{-\gamma x}} \right] J_0(\lambda x) \, d\lambda \, dt
\]  
(5.32)
5.7.2 Rod Electrode Resistance buried in a Multi layer Media

From [37] the earth resistance for a deep driven rod can be expressed as the ratio between the potential at the surface of the rod and the current flowing in the rod. That is,

\[ R = \frac{V_0(a)}{I} \]  
(5.33)

Where,

\( a \) - radius of the rod

Therefore, from equation (5.32),

\[ R = \frac{1}{2\pi} \sum_{\ell=1}^{n} \frac{1}{h_{\ell-\ell} - \ell} \sum_{k=1}^{n} \alpha_{k} e^{-\alpha \ell} + \beta_{k} e^{-\beta \ell} \int_{0}^{\infty} \frac{J_{\ell}(\ell x) d\ell \ell}{\alpha x - \beta x e^{-\beta x}} \]  
(5.34)

In order to evaluate the theoretical values for the Case Study in section 5.8 the equations (5.32) and (5.34) are used. The Mathematica 5.0 software is used for the calculations. To evaluate the compatibility of using Mathematica, the software output is compared with the results given in [37].

Table 5.2 compares the calculated results from equation (5.34) using the Mathematica 5.0 software and the results given in [37]. The results obtained from Mathematica calculations reveal close agreement with the results in [37] with maximum error in the order of 0.7%. Thus, through the use of the Software I proceeded to calculate the earth resistance for the earth electrode.

<table>
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<th>h</th>
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<th>Mathematica;R2</th>
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<th>(R-R2)/R%</th>
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</tbody>
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Table 5.2 - Error of calculated Electrode Resistance