Jeddah Soil Resistivity and Grounding Resistance

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Abstract: The use of electricity brings with it an electric shock hazard for humans and animals, particularly in the case of defective electrical apparatus. In electricity supply systems, it is therefore a common practice to connect the system to ground at suitable points. Thus in the event of a fault, sufficient current will flow through and operate the protective system, which rapidly isolates the faulty circuit. Therefore, the connection to ground is required to be of sufficient low resistance. Because the topography of Jeddah city includes coastal, sandy, and rocky areas, the soil resistivity will differ across city locations, thus affecting the efficiency of the grounding circuit. To design an efficient grounding circuit, we conducted experiments to measure the soil resistivity for each soil type at different locations, taking into account factors such as salt, moisture, and density. The results of these experiments are preliminary measures for designing grounding grid systems for different topographical areas.

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1.Introduction

It is a statutory obligation in most countries, as well as a technical requirement, that all parts of an electric power system shall have an effective connection to earth. This implies that each electrically separate part of a system, which is magnetically coupled to other parts at the transformation points, must be separately earthed. In the words of the definition contained in the 1937 Electricity Supply Regulations, which remains relevant today, “A connection to earth means connected with the general mass of earth in such a manner as to ensure at all times an immediate and safe discharge of energy.”

A ground system that provides adequate current-carrying capacity and a low resistance path to an earthing connection will dissipate, isolate, or disconnect overpotential areas resulting from overcurrents or surge overvoltages. Equipment-grounding conductors under normal conditions carry no current. The only time they carry current is under abnormal conditions when an electrical appliance or piece of electrical equipment is faulty and has become a potential shock or fire hazard. Under fault conditions, the grounding conductor that is connected to the outer shell or sheet metal of the equipment or appliance must be able to provide a very low resistance path back to the source of the power so that sufficient current will flow, causing a breaker or fuse to open the circuit and automatically disconnect the hazard from the system [1–11].

2. Methods of Measuring Soil Resistivity

The techniques for measuring soil resistivity are essentially the same whatever the purpose of the measurement. However, interpretations of the recorded data may vary considerably, particularly where soils with nonuniform resistivity are encountered. Added complexity caused by nonuniform soils is common, and in only a few cases does the soil resistivity remain constant with increasing depth.

Often, at a site where a grounding system is to be installed, extensive civil engineering work must be carried out. This work usually involves geological prospecting, which results in considerable amounts of information on the nature and configuration of a site’s soft ground. Such data may be of considerable help to electrical engineers because soil resistivity may vary widely within short distances and changes with depth below the ground surface. Thus, if a soil sample method is used, many samples must be taken to obtain an accurate map of soil resistivity in the area. Soil sample tests are also more time-consuming than other measurements.

2.1 Two-Point Method

Rough measurements of the resistivity can be made in the field with the Shepard soil resistivity apparatus and similar two-point methods. The apparatus consists of one small and one smaller iron electrode, both attached to an insulating rod. The positive terminal of a battery is connected through an ammeter to the smaller electrode, and the negative terminal is connected to the other electrode. The instrument can be calibrated to read directly in ohm-centimeters at nominal battery voltage. This type of apparatus is easily portable, and with it, a number of measurements can be made within a short time on small volumes of soil by driving the electrodes into the ground or into the walls or bottom of excavations.

2.2 Variation of Depth Method

The variation of depth method, sometimes called a three-point method, is a ground resistance test carried out several times, and each time, the depth of burial of the tested electrode is increased by a given increment. The purpose of this is to force more test current through deep soil. The measured resistance value will then reflect the variation of resistivity at increased depth. Usually the tested electrode is a rod. Rods are preferred over other types of electrodes because rods offer two important advantages:

1. The theoretical value of ground rod resistance is simple to calculate with adequate accuracy, and therefore the results are easy to interpret.
2. It is usually easy to drive a rod into soft ground.

The ground resistance of the rod buried in a uniform soil is given by

$$\mathrm{R} = \frac{\rho}{2\pi l} \ln \frac{2l}{r} \tag{1}$$

or

$$\mathrm{R} = \frac{\rho}{2\pi l} \ln\left(\frac{4l}{r} - 1\right) \tag{2}$$

where the tested ground is a rod driven at depth l, and the rod radius r is smaller than l. For other forms of electrodes, the calculations will be similar.

2.3 Four-Point Method

The most accurate practical method of measuring the average resistivity of large volumes of soil is the four-point method [1]. Small electrodes are buried in four small holes in the earth, all at depth b and spaced (in a straight line) at intervals a. A test current I is passed between the two outer electrodes, and the potential V between the two inner electrodes is measured with a potentiometer or high-impedance voltmeter. V/I then provides the resistance R in ohms. Two variations of the four-point method are often used: the equally spaced or Wenner arrangement, and the unequally spaced or Schlumberger–Palmer arrangement.

With the Wenner arrangement, the electrodes are equally spaced (Figure 1a). If a is the distance between two adjacent electrodes, then the resistivity ρ in terms of the length units in which a and depth b are measured is

$$\rho = \frac{4\pi aR}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \tag{3}$$

However, in practice (Figure 1b), four rods are usually placed in a straight line at intervals a, driven to a depth not exceeding $0.1a$. If $b = 0$, the formula provides the approximate average resistivity of the soil in relation to a:

$$\rho = 2\pi aR \tag{4}$$

One shortcoming of the unequally spaced or Schlumberger–Palmer arrangement is the rapid decrease in the magnitude of potential between the two inner electrodes when their spacing is increased to relatively large values.

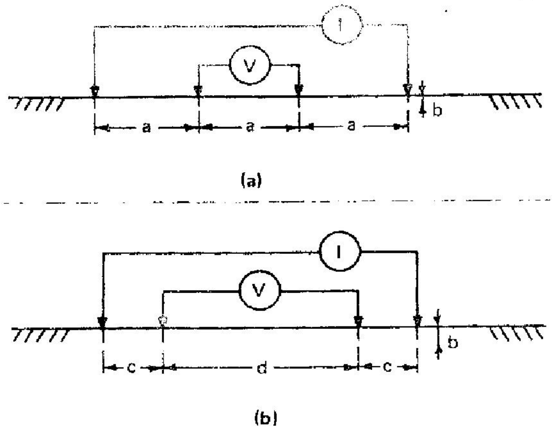

Figure 1. Four-point method: (a) equally spaced and (b) unequally spaced

3. Ground Impedance

Ground impedance measurements must be performed to determine the actual impedance of the ground connections to establish the rise in ground potential and to obtain the data necessary for designing protection for buildings, the equipment inside them, and any personnel. The ground connections of power systems must be studied to determine variations in ground potential that may be encountered during ground fault conditions, so as to ensure personnel safety, adequacy of insulation, and continuity of service.

4. Theoretical Value of Ground Resistance

Calculated or theoretical values of the resistance of an electrode to remote earth may vary considerably from the measured values because of the following factors:

1. Adequacy of the analytical equations used in the resistance calculations.
2. Conditions of the soil at the time the measurement is made.
3. Inaccurate or insufficient extent of the resistivity survey, for example, number and dispersal of tests, probe spacing, and inadequacy of the instrumentation used.

4. Presence in the soil of adjacent metallic buried structures and ground wires, which may divert a substantial amount of the test current.

To decrease the sources of error in establishing the relationship between earth resistivity and ground resistance, it is advisable to perform resistivity and resistance measurements under similar weather and moisture conditions. If the measured values are used as data for the design of a grounding electrode, the measurements should be carried out under varying weather conditions. This will help the designer to establish the most restrictive or limiting case, particularly for small grounds, which are influenced by seasonal changes of weather.

5. Methods of Measuring Ground Impedance

Several methods may be used to find grounding resistance.

5.1 Two-Point Method (Ammeter–Voltmeter Method)

In the ammeter–voltmeter method, the total resistance of the unknown ground and an auxiliary ground is measured. The resistance of the auxiliary ground is presumed to be negligible in comparison with the resistance of the unknown ground, and the measured value in ohms is called the resistance of the unknown ground.

5.2 Three-Point Method

The three-point method involves the use of two test electrodes, the resistances of which are designated r_2 and r_3, and the electrode to be measured, which is designated r_1. The resistance between each pair of electrodes is measured and designated r_{12}, r_{13}, and r_{23}, respectively (where, for example, $r_{12} = r_1 + r_2$). Solving the simultaneous equations, it follows that

$$r_1 = \frac{(r_{12}) - (r_{23}) + (r_{13})}{2} \tag{5}$$

Therefore, by measuring the series resistance of each pair of ground electrodes and substituting the resistance values in Eq. (5), the value of r_1 may be established. If the two test electrodes are of materially higher resistance than the electrode being measured, the errors in the individual measurements will be greatly magnified in the final result. For the measurement, the electrodes must be at some distance from each other, otherwise absurdities may arise in the calculations, such as zero or negative resistance. In measuring the resistance of a single driven electrode, the distance between the three separate ground electrodes should be at least 5 m, with a preferable spacing of 10 m or more. For larger-area grounding systems, which are presumably of lower resistances, spacings in the order of the dimensions of the grounding systems are required as a minimum.

5.3 Ratio Method

In the ratio method, the resistance of the electrode being measured is compared with a known resistance, usually by using the same electrode configuration as that used in the fall-of-potential method (see Section 7). Because the ratio method is a comparison method, the ohm readings are independent of the test current magnitude if the test current is sufficiently high to provide adequate sensitivity.

6. Staged Fault Tests

Staged high-current tests may be required for those cases where specific information is desired about a particular grounding installation. Moreover, ground impedance may be determined as auxiliary information at the time of actual ground faults by using an oscillograph or one element of an automatic-station oscillograph.

In either case, the instrumentation is the same. The object is to record the voltage between selected points on one or more oscillograph elements. The voltages to be recorded will probably be of such great magnitude that potential step-down transformers will be required. The maximum voltages that can be expected and thus the ratios of the potential transformers required may be determined in advance of the staged tests by using the fall-of-potential method at practical values of test current.

Another important consideration is the calibration of the oscillograph circuit, which is composed of a potential transformer with a possible high resistance in the primary. This resistance is composed of the remote potential ground in series with a long lead. A satisfactory calibration of the deflection of the oscillograph element may be made by inserting a measured voltage in the primary circuit in series with the lead and the remote potential ground as used during the test. The location of the actual points to be measured is dependent on the information desired, but in all cases, allowance must be made for coupling between test circuits.

7. Fall-of-Potential Method

The fall-of-potential method has several variations and is applicable to all types of ground impedance measurements. Therefore, the measured value is impedance, although the terminology often used is “resistance.” The method involves passing a current into the electrode to be measured and noting the influence of this current in terms of the voltage between the ground being measured and a test potential electrode.

A test current electrode is used to permit a current to be passed into the electrode to be tested (Figure 2). The current *I* through the tested electrode E and the current electrode C results in earth surface potential variations. The potential profile along the C, P, and E direction will appear as shown in Figure 3. Potentials are measured with respect to the ground being measured, E, which is assumed for convenience at zero potential.

The fall-of-potential method consists of plotting the ratio of $V/I = R$ as a function of probe spacing X. The potential electrode is moved away from the ground under measurement in steps. A value of impedance is obtained at each step. This impedance is plotted as a function of distance, and the value in ohms at which this plotted curve appears to level out is taken as the impedance value of the ground under measurement (Figure 4). This rule of thumb must be applied carefully because it provides satisfactory results only if a flat portion has been established clearly.

A representative curve for a large grid ground is shown in Figure 5. The data for this figure were taken from a test conducted on a station that had a ground grid of approximately 125 m × 150 m. Distances were measured from the station fence; hence the impedance is not zero at zero distance on the curve. Curve B was obtained with the potential probe located between E and C. Curve A was obtained with the potential probe located at the opposite side with respect to the current electrode C.

The test results show the presence of a mutual resistance between the current electrode and the station ground, which is why curve B does not level out. Curve A does appear to level out and may be used to obtain a lower limit for the impedance value of the electrode being measured.

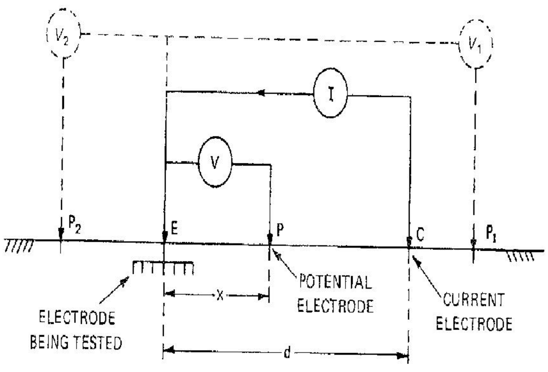

Figure 2. Fall-of-potential method

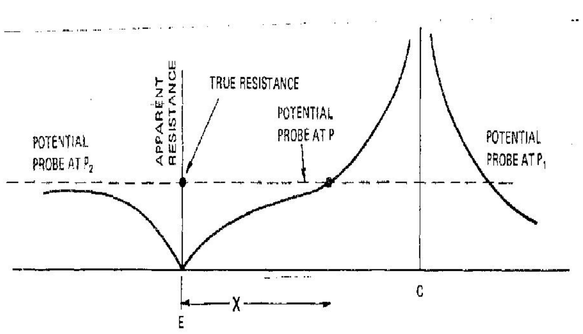

Figure 3. Apparent resistance for various spacing *X*

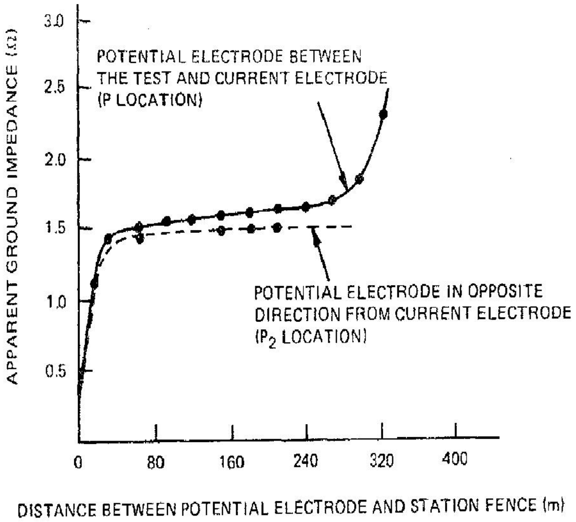

Figure 4. Case of a high-impedance ground system

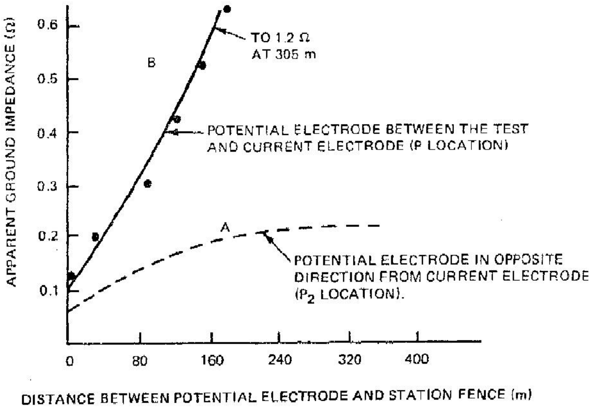

Figure 5. Case of a low-impedance ground system

8. Experimental

8.1 Factors Affecting Soil Resistivity

Earth resistivity varies not only with the type of soil but also with temperature, moisture, and salt content (Figure 6). The resistivity of the earth increases slowly with decreasing temperature from 25 °C to 0 °C. Below 0 °C, the resistivity increases rapidly. Usually, there are several layers of soil, each having a different resistivity.

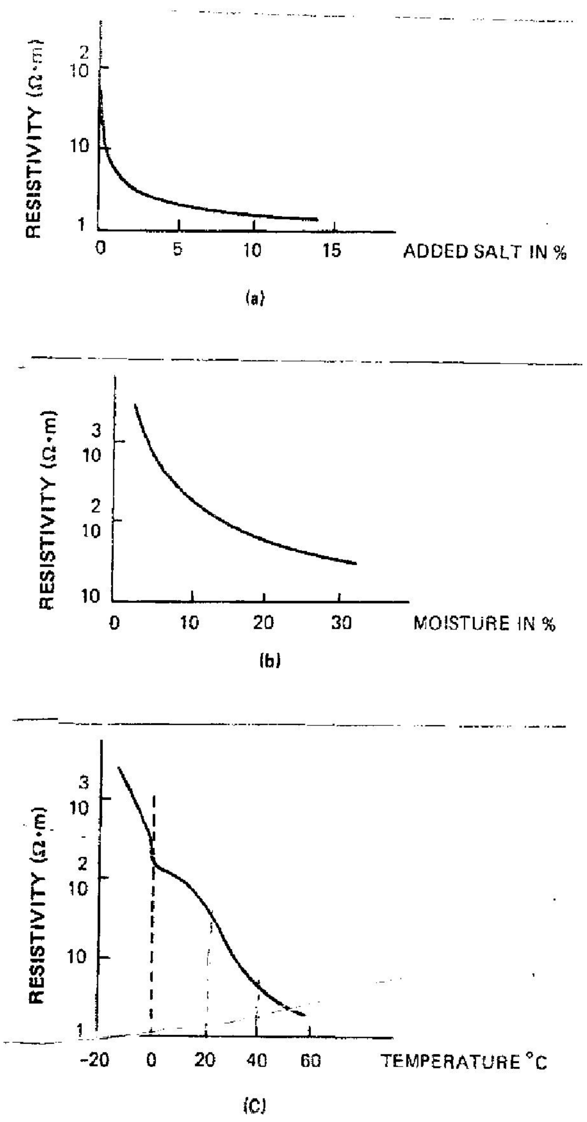

Figure 6. Earth resistivity variations with (a) salt, (b) moisture, and (c) temperature

Lateral changes may also occur, but in general, these changes are gradual and negligible, at least in the vicinity of the site concerned. In most cases, the measurement will show that the resistivity ρ is mainly a function of depth z. For purposes of illustration, let us assume that this function may be written as

$$\rho = \phi(z) \tag{6}$$

The nature of the function ϕ is in general not simple; therefore, interpretation of the measurements will consist of establishing a simple equivalent function ϕ_e to provide the best approximation.

The most common test method is the Wenner four-probe method, which is used to measure large volumes of soil. If test pits are dug, there will be an opportunity to measure subsurface soils directly. If the values of all soil resistivity data points fall within 30% of the average value, a uniform soil assumption can be made, and a single value for soil resistivity will need to be chosen. If a uniform soil resistivity assumption cannot be made, then the final design should be based on an analysis technique that is able to incorporate a two-layer soil model.

Soil resistivity is affected by many factors, but the factors that have significant effects on soil resistivity are soil type, soil density, moisture content, salt content, and temperature.

We conducted experiments to describe the relationships between soil resistivity and the abovementioned factors.

8.2 Experiment Array Design

To conduct the experiment, we designed an array of length 15 cm, diameter 4 cm, and thickness 3 mm to allow soil resistivity inside the array to be measured in terms of weight and density. The array should meet the following conditions:

1. The array should be cleaned regularly.
2. The cylinder should be empty and composed of nonconducting material.
3. The array should be closed at both ends by conducting material.

The basic principle is to fill the array with soil and close both ends, then measure the resistance of the soil inside the array by using an ohmmeter. The soil resistivity can be calculated by

$$R = \frac{L}{A}\rho \tag{7}$$

where R is the resistance of the soil (Ω); ρ is the soil resistivity (Ωm); L is the array length (m); and A is the cross-sectional area of the array (m^2).

The experiment should be repeated with many samples of soil to observe the effect of each factor on soil resistivity.

8.3 Effect of Moisture

To check the level of soil moisture, the following steps should be carried out:

1. Place a sample of soil in an oven for 24 h.
2. Fill the array with the sample in three stages to avoid changing the soil density inside the array.
3. Add 5% of water to the soil and mix it well.
4. Use an ohmmeter to measure the resistance of the mixture.

5. Repeat steps 3–4 with different percentages of water (7%, 10%, 12%, and so on).

Table 1 shows the results of measurements of soil resistivity versus soil moisture. Note that the soil resistivity decreases with increasing moisture.

Table 1. Soil resistivity versus moisture

Added water (kg)	Mixture (Ω)	Resistance (Ωm)	Resistivity
5%	344.610	2520	21.62
7%	351.174	1403	12.04
10%	631.020	1027	8.81
12%	367.584	850	7.29
15%	377.430	665	5.71
17%	383.994	500	4.89
20%	393.840	500	4.29

8.4 Effect of Density

To check the level of soil density, the following steps should be carried out:

1. Add a sample of soil to a percentage of water and mix well.
2. Place the mixture in the oven for 24 h.
3. Fill the array with the mixture in three stages to avoid changing the soil density inside the array.
4. Calculate the soil density by using the equation: density = weight / volume.
5. The resistance of the mixture can be measured by using the ohmmeter, and the soil resistivity can then be calculated by using Eq. (7).
6. Repeat steps 3–5 with different densities of soil.

Table 2 shows the results of measurements of soil resistivity versus soil density.

Table 2. Soil resistivity with changing soil density

Soil weight (g)	Density (g/m^3)	Resistance (Ω)	Resistivity (Ωm)
335	1.6996	67.86	582.29
350	1.7757	60.6	520
380	1.9280	49.1	421.32
410	2.080	41.4	355.25

8.5 Effect of Salt Content

Chemical salt percentage is a significant factor affecting the value of soil resistivity. A high salt percentage results in low resistivity, and a low salt percentage results in high resistivity.

To obtain accurate resistivity measurement results, we selected three sites in the city of Jeddah, Saudi Arabia, according to their difference in soil type. The sites were Obhur, Alhamadania, and Harazat. The experiment was carried out at the Earth Science College laboratory at King Abdulaziz University. The experimental steps were as follows:

1. 50 ml of water was added to 0.5 kg of soil.
2. The mixture was placed into an oven and heated for 30 min then allowed to cool for 30 min.
3. The mixture was reheated for a further 30 min then left to cool for 60 min.

Table 3 shows the salt percentage measured at each of the three sites in Jeddah city.

Table 3. Percentage of salt content at the three sites

Salt %	Obhur	Alhamadania	Harazat
Na	0.101	0.623	0.032
CL	0.0403	0.2653	0.0141
K	0.012	0.05	0.010
HCO_3	2.1460	0.4183	0.1037
SO_4^{++}	0.0094	0.1789	0.0377
Ca^{++}	1.2989	0.1073	0.04333
Mg^{++}	1.2742	0.109	0.06428

We observed that the Obhur site, which is in close proximity to the sea, has the highest salt percentage of among the three locations, and that the Harazat site, which is the furthest from the sea, has the lowest salt percentage (Table 3). This indicates that Obhur has the lowest soil resistivity and that Harazat has the highest soil resistivity among the three locations.

9. Conclusion

The purpose of this research was to prepare a comprehensive database reflecting soil resistivities in different areas of Jeddah and to design a reliable grounding grid system for each area. For this purpose, each city was divided into zones, and electrical soil resistivity were measured for each zone during different seasons. The investigation offers a laboratory method to describe the relationships between electrical soil resistivity and factors affecting it such as moisture, density of soil, and salt content, and the experimental results show that the electrical soil resistivity decreases nonlinearly with increasing soil moisture and soil density. Subsequent research will focus on the design of substation grounding grids.

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