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Soil Resistivity Data Computations; Single and Two - Layer Soil Resistivity Structure and Its Implication on Earthing Design

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***Abstract*—**Performing High Voltage (HV) tasks with a multi craft work force create a special set of safety circumstances. This paper aims to present vital information relating to when it is acceptable to use a single or a two-layer soil structure. Also it discusses the implication of the high voltage infrastructure on the earth grid and the safety of this implication under a single or a two-layer soil structure. A multiple case study is investigated to show the importance of using the right soil resistivity structure during the earthing system design.

***Keywords*—**Earth Grid, EPR, High Voltage, Soil Resistivity Structure, Step Voltage, Touch Voltage.

I. Introduction

HIGH voltage infrastructure necessitates earthing design to warrant the safety and the acquiescence of the system to the confined standards and regulations. Earthing system presents a safe working environment for workers and people passing by during a fault or a malfunction in the power system. Soil resistivity structure is one of the main elements that have a burly impact on the design. The change in the soil resistivity structure can pilot to a complex earthing design.

By nature, the soil body consists of horizontal and vertical layers. These layers consist of variable thicknesses, which differ from the parent materials in their texture, structure, consistence, color, and in other chemical, biological and physical characteristics [1-2].

This paper endeavours to present a general overview of various ways of determining the soil resistivity structure using the field test data. It also clarifies when it is acceptable to use a single layer or a two-layer soil structure when it comes to earthing design. A case study is conducted and the results are presented.

II. Theoretical Study

In engineering, soil is referred to as regolith, or loose rock material. Strictly speaking, soil is the depth of regolith that influences and has been influenced by plant roots.

Soil resistivity is a measure of a soil's ability to retard the conduction of an electric current. The electrical resistivity of soil can affect the rate of galvanic corrosion of metallic structures in contact with the soil. Higher moisture contents or increased electrolyte concentration can lower the resistivity and increase the conductivity. Soil resistivity values typically a range from about 2 to 10000 Ω·m, but more extreme values are not unusual.

Table I shows the different type of soil and its typical soil resistivity. It is rare to find an area that consists of one type of soil or of one layer. From a soil resistivity perspective, it is acceptable to use two layers when determining the earth grid assessment [3].

TABLE I
TYPICAL SOIL RESISTIVITY OF VARIOUS TYPES OF SOIL

Type of Soil or water	Typical Resistivity (Ω / m)
Sea Water	2
Clay	40
Ground well and spring water	50
Clay and Sand mix	100
Shale, Slates, Sandstone	120
Peat, Loam and Mud	150
Lake and Brook Water	250
Sand	2000
Morane Gravel	3000
Ridge Gravel	15000
Solid granite	25000
Ice	100000

As the mass of earth plays a part in any electrical infrastructure, it also plays an important role in absorbing the fault and malfunction energy of these plants. Soil resistivity structure is the key in this operation, determining the soil resistivity will establish the conductivity of the ground thus determining the capability of the soil to form an easy path for the fault or malfunction in the electrical system.

Resistance is the property of a conductor which opposes electric current flow when a voltage is applied as shown in equation 1:

$$V = I \times R \tag{1}$$

Low resistance is known as a good conductor and high resistance are known as a bad conductor.

The resistance R depends on the resistivity of the conductor (medium) as shown in equation 2:

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$$R = \frac{\rho \times L}{A} \tag{2}$$

Where
ρ is the resistivity of the conductor (medium)
L is the length of the conductor
A is the cross section area

Fig. 1 demonstrates the different soil structure that can impact the electrical design. Based on IEEE 80 standard, two layer structures is sufficient for conducting an acceptable design.

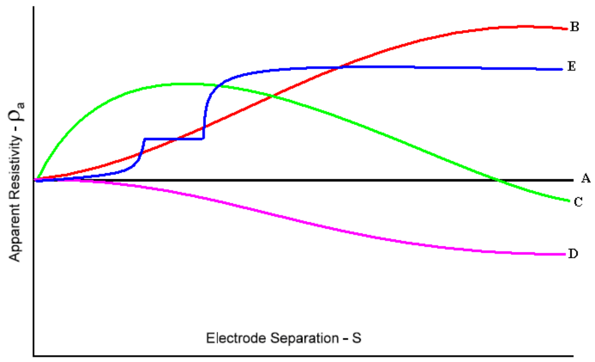

Fig. 1 IEEE 80 soil structure

- Curve (A) represents homogenous resistivity
- Curve (B) represents a low resistance layer overlaying a higher resistivity layer
- Curve (C) represent a high resistivity layer between two low resistivity layers
- Curve D) represents a high resistivity layer overlaying a lower resistivity layer
- Curve (E) represents a low resistivity layer over a high resistivity layer with vertical discontinuity

III. Soil Resistivity Structure Field Test

The most three popular methods to perform soil resistivity test are: [4-5]

- Wenner Method
- Schlumberger Array
- Driven Rod Method

The WennerMethod is the most popular one due to the following reasons [6-7]:

- WennerMethod is capable of obtaining the data from deeper layers without driving the test pins to those layers
- No heavy equipment is needed to perform this test
- The results are not highly affected by the resistance of the test pins
- The results are not affected by the holes created by the driving test pins

Fig. 2 shows WennerMethod arrangement

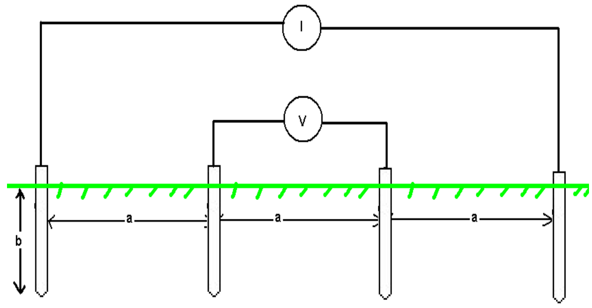

Fig. 2 Wenner Method for Soil Resistivity Test

IV. Soil Resistivity Structure Computation

Interpreting and computing the soil model structure using the measured data is one of the most difficult parts. It is important to derive a soil model analogous from the real one. The most frequently used soil resistivity structures are the uniform model and the two-layer model. According to IEEE 80, two layers SRS are often a good approximation of many soil structures. This computation can be achieved manually or by using aided computer software.

A uniform SRS should only be used if the variation in the measured apparent resistivity is low, this has a rare occurrence in practice. If a large variation occurs, the uniform soil is unlikely to yield accurate results. According to IEEE standard, more accurate representations of the actual soil conditions can be obtained by the use of the two- layer SRS model.

The uniform soil can be determined using equation 3

$$\rho = \frac{\rho_1 + \rho_2 + \ldots\ldots\rho_i}{N_i} \tag{3}$$

Where

ρ_i is the apparent soil resistivity measured at different distances

N_i is the number of soil resistivity test

Another approach is established in determining the uniform soil resistivity as shown in equation 4:

$$\rho = \frac{\rho_{\max} + \rho_{\min}}{2} \tag{4}$$

Where

$\rho_{\max}$ is the maximum apparent resistivity value measured

$\rho_{\min}$ is the minimum apparent resistivity value measured

The usage of equation 4 is not recommended for a ground grid without ground rods.

The characteristic determinations of the two layer soil structure are more complicated, the two -layer soil model can be approximate by using graphical methods described in Sunde's chart. Fig. 3 illustrates the chart:

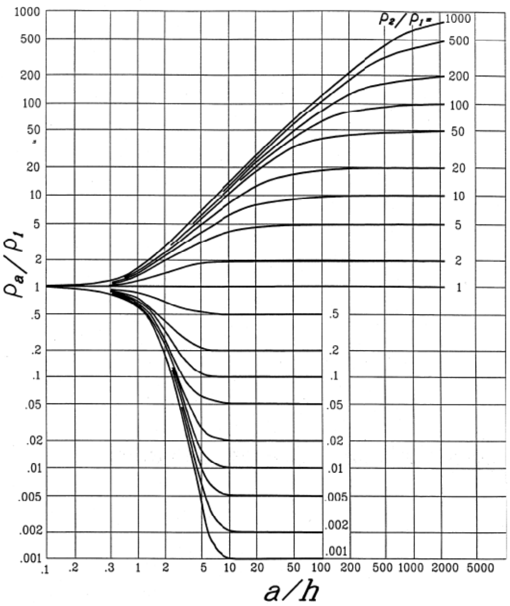

Fig. 3 Sunde's chart method to determine the two layer SRS

The two- layer structure consists of the characteristics shown in Table II:

TABLE II
TWO- LAYER SOIL RESISTIVITY

Layers Number	Resistivity (Ohm.m)	Thickness of layers (meters)
1	ρ_1	H
2	ρ_2	Infinite

V. SRS AND EARTHING DESIGN

Fine interpretation of the soil structure is very important to ease the earthing design and achieve the adequate design with low cost. For example, if high soil resistivity is presented on top and low resistivity on bottom, it is effective to drive the electrode to reach the low resistance layer. During the homogenous resistivity approach, the entire earthing system will be exposed to one type of soil resistivity; this could lead to error especially if the change in soil layers resistivity is large. Also the safety compliance assessment will use the average computed soil value; this could be deviated from the actual top soil value.

During the two layer approach, the electrode will be exposed to different soil resistivity which represents a more realistic approach; also the safety assessment will address the top layer resistivity which in its turn represents a more practical situation. Understanding the soil layers resistivity supports the designer in determining the type of earth grid that yields to an adequate solution, below is a couple of cases under different soil structures:

- Low resistance layer overlaying higher resistivity layer, mesh grid will have a better influence than driving electrodes into the high resistivity layer.
- High resistivity layer overlaying a lower resistivity layer, a deep electrode used to reach the lower resistivity layer will enhance the performance of the earth grid.

CDEGS is one of the few available software that can be used to compute the soil resistivity structure using the field test. Fig. 4 shows an output computation for a field test using RESEP in CDEGS engineering software, it details the depth, the upper layer, and the bottom layer of the soil structure, CDEGS follow IEEE procedures

When using two-layer soil structure to determine the grid resistance, it is important to determine the reflection factor K. Equation 5 shows the computation of the reflection K

$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \tag{5}$$

Where

ρ_2 is the bottom layer soil resistivity

ρ_1 is the top layer soil resistivity

The earth grid consists of a single electrode, multiple electrodes, mesh grid or combination of mesh and electrodes. Two types of formulas exist to compute the earth grid:

- Formulas for single layer soil structure. [2]contains information in regards to these equations.
- Formulas for two-layer soil structure. These formulas are shown below

As discussed earlier, soil structure consists of multiple layers. For several soil structures, in order to yield an acceptable design, two layers shall be used throughout the earth grid resistance calculation. Applying two-layer soil structure during the earth grid calculation could be concluded using two methods:

- Calculate an apparent soil resistivity that can be used in the same equations mentioned in [8], the apparent soil resistivity utilizes the characteristics of the two-layer structure as shown in equations 6 and 7.
- Calculate the earth grid resistance using equations 8 to 13.

For the first method, there are two formulas as shown below:

For a negative reflection coefficient K

$$\rho_a = \frac{\rho_1}{\left(1 + \left(\frac{\rho_1}{\rho_2} - 1\right) \times \left(1 - e^{\frac{-1}{-k(d+2h)}}\right)\right)} \tag{6}$$

For a positive reflection coefficient K

$$\rho_a = \rho_2 \left(1 + \left(\frac{\rho_2}{\rho_1} - 1\right) \times \left(1 - e^{\frac{-1}{k(d+2h)}}\right)\right) \tag{7}$$

Where
d is the depth of the top layer
h is the grid depth

The calculated apparent soil resistivity will be applied in the single layer equations when determining the grid resistance.

For the second method, the calculation is divided into three types:

- Mesh Grid calculations
- Electrode calculations
- Combination of mesh and electrodes

This paper discusses the electrodes calculation process.

R_1 represents the resistance related to the top layer, R_2 represents the resistance related to the bottom layer

$$R_1 = \frac{\rho_1}{h-h_g} g_0 \frac{F}{N} + \frac{\rho_1}{h}\phi \tag{8}$$

$$R_2 = \frac{\rho_2}{l+h_g-h} g_0 \frac{F}{N} \tag{9}$$

The total resistance can be found by considering R_1 parallel to R_2

Where

g_0 is a function that can be found using equation

a is the radius of the driven rod

h_g is the depth of the grid from the ground level

h is the depth of the top layer

F is the factor for the N rods, can be found using equation

l is the length of the electrode

ϕ is a function as shown in equation

$$g_0 = \frac{1}{2\pi}\left(\ln\frac{2l}{a} - 1 + \frac{\ln 2}{1+\dfrac{(4\ln 2)h_g}{l}} \right) \tag{10}$$

$$F = 1 - \left(N - \frac{1}{\sqrt{N}} \right)\frac{R_s}{R_l} \tag{11}$$

$$\phi = \frac{\dfrac{1}{2\pi}\left(\ln\dfrac{1}{1-k}\right)}{\sqrt{\left(\dfrac{N}{F}-1\right)^2\left(\dfrac{l+h_g}{h}\right)^2+1}} \tag{12}$$

$$\frac{R_s}{R_l} = \frac{\sqrt{\dfrac{l}{r}\left[\left(0.5^3\right)+\left(\dfrac{l}{l+0.5r}\right)^3\right]^{\frac{1}{3}}}}{2\pi g_0} \tag{13}$$

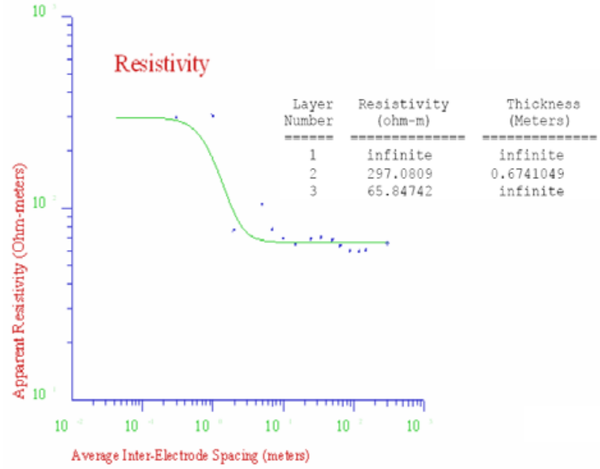

Fig. 4 CDEGS computation of the SRS

VI. Case Study

Multiple soil resistivity field tests are conducted at different locations, Table III represents the field data. Clearance time is given to be 500ms with fault current of 1000A. Using equation 3 to determine the average soil structure for these 5 different conditions, CDEGS is used to determine the two-layer soil structure for these proposed case studies.

Field Study #1, the single layer soil resistivity value is shown below. Fig. 5 shows the output of RESEP software in CDEGS, and it also shows the two- layer characteristics of the measured soil resistivity data.

$$\rho = 57.97\Omega m$$

Field Study #2, the single layer soil resistivity value is shown below. Fig. 6 shows the output of RESEP software in CDEGS, and it also shows the two layers' characteristics of the measured soil resistivity data

$$\rho = 603.88\Omega m$$

TABLE III
Field Data Used for Case Study

Probe S (m)	#1 (Ωm)	#2 (Ωm)	#3 (Ωm)	#4 (Ωm)	#5 (Ωm)
1	27.8	1086	9.96	39.1	36.4
2	23.3	921	12.9	36.6	37.9
4	39.9	603	10.6	30.5	50.4

6	31.8	535	13.0	31.3	NA
8	40.5	533	14.8	39.0	78.3
10	48.8	555	15.9	45.5	NA
14	62.3	512	17.7	48.7	117.0
18	79.1	436	22.0	50.7	135.0
26	106	254	32.3	53.4	158.1

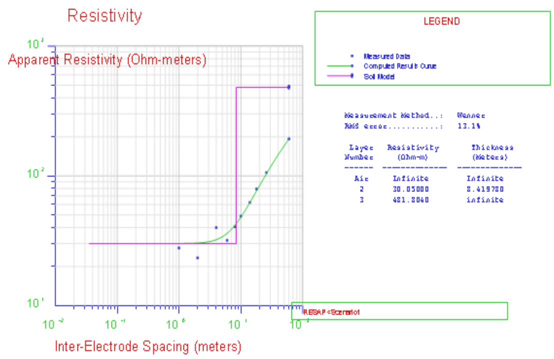

Fig. 5 CDEGS output for case study #1

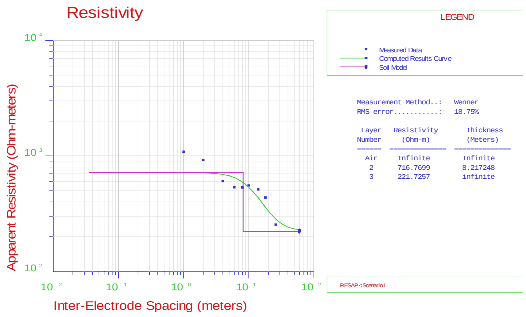

Fig. 6 CDEGS output for case study #2

Field Study #3, the single layer soil resistivity value is shown below. Fig. 7 shows the output of RESEP software in CDEGS, and it shows the two-layer characteristics of the measured soil resistivity data

$$\rho = 16.57\Omega m$$

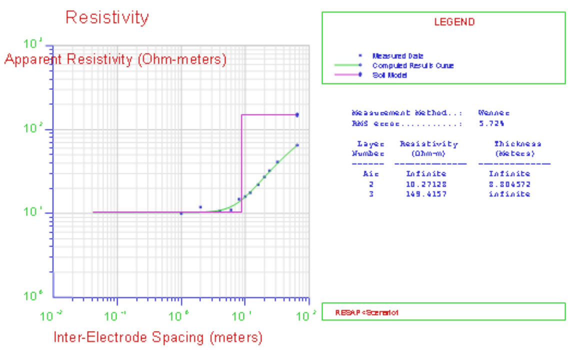

Fig. 7 CDEGS output for case study #3

Field Study #4, the single layer soil resistivity value is shown below. Fig. 8 shows the output of RESEP software in CDEGS, and it also shows the two- layer characteristics of the measured soil resistivity data

$$\rho = 41.64\Omega m$$

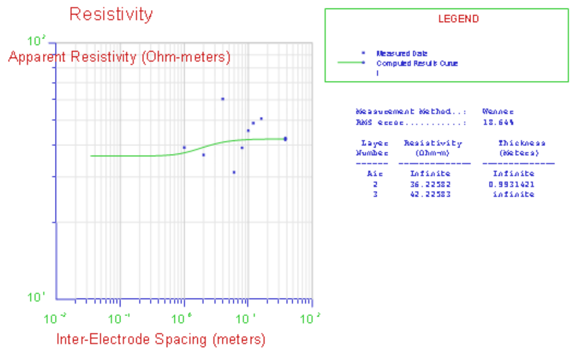

Fig. 8 CDEGS output for case study # 4

Field Study #5, the single layer soil resistivity value is shown below. Fig. 9 shows the output of RESEP software in CDEGS, and it shows the two-layer characteristics of the measured soil resistivity data

$$\rho = 87.58\Omega m$$

Table IV represents the allowable touch voltage under 500ms clearance time with the computed average soil resistivity. Table V represents the allowable touch voltage under two-layer soil resistivity structure. The variation in the allowable safety limits can be neglected when using either a single layer or a two-layer soil structure.

Fig. 10 represents the earth grid of the designed substation; the earth grid consists of mesh and electrodes. Table VI represents the grid resistance computation under the 5 soil cases. The variation in the computed earth grid under a single layer and two layers are significant. This difference has a huge impact on the EPR of the designed substation; Fig. 11 shows the EPR profile.

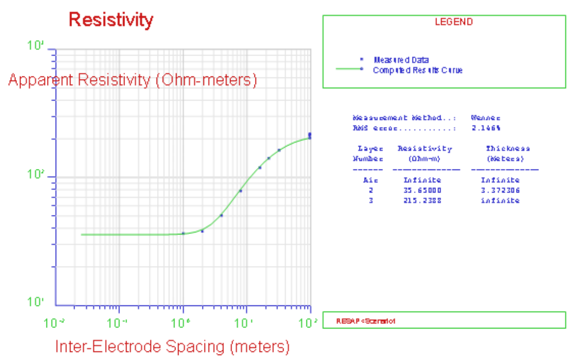

Fig. 9 CDEGS output for case study # 5

TABLE IV
ALLOWABLE STEP AND TOUCH VOLTAGE UNDER THE AVERAGE SOIL RESISTIVITY

Case Study	#1	#2	#3	#4	#5
Touch Voltage	178	312.6	168.1	174.3	185.4
Step Voltage	220.1	758.5	180.3	204.4	249.6

TABLE V
ALLOWABLE STEP AND TOUCH VOLTAGE UNDER 2 SOIL LAYERS

Case Study	#1	#2	#3	#4	#5
Touch Voltage	171.4	340.2	166.5	172.9	172.6
Step Voltage	193.5	868.8	173.8	199.4	198.5

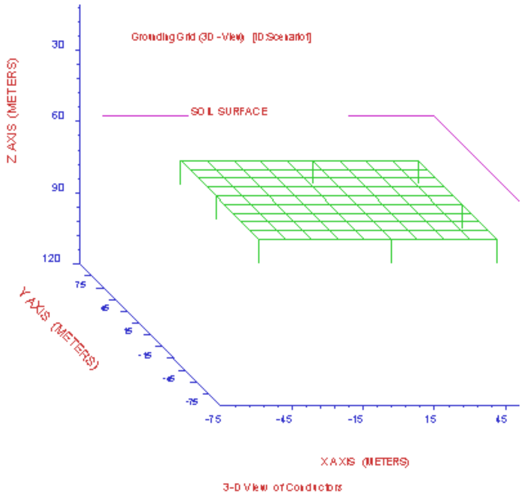

Fig. 10 Earth grid layout

TABLE VI
COMPUTED EARTH GRID RESISTANCE

Case Study	R_{Grid} #1	R_{Grid} #2	R_{Grid} #3	R_{Grid} #4	R_{Grid} #5
Single layer	0.26	2.75	0.07	0.19	0.39
Two layers	0.79	1.54	0.25	0.18	0.68

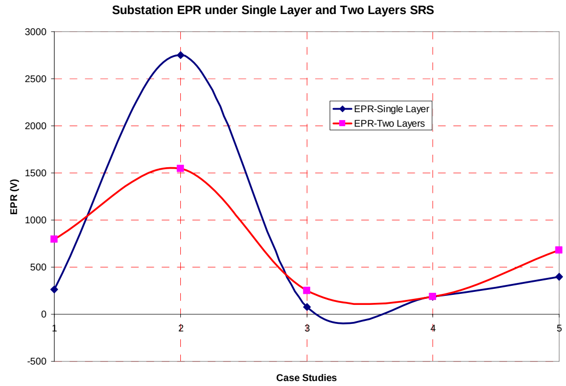

Fig. 11 Computed EPR under different soil Structure

VII. CONCLUSION

This paper highlights the importance of using a two-layer soil structure when it comes to determine the earth grid resistance and EPR. Among the five case studies, only in case study number 4, apparent soil resistivity method can be approved.

Using apparent soil structure in cases 1, 3 and 5 will lead to a more expensive system, and using the apparent soil structure in case study 2, leads to a non-compliance system.

This paper also shows that apparent soil resistivity structure can be used when small deviation occurs in the field test data as illustrated in case study number 4.

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