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Estimation of apparent soil resistivity for two-layer soil structure

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Abstract
High voltage (HV) earthing design is one of the key elements when it comes to safety compliance of a system. High voltage infrastructure exposes workers and people to unsafe conditions. The soil structure plays a vital role in determining the allowable and actual step/touch voltage. This paper presents vital information when working with two-layer soil structure. It shows the process as to when it is acceptable to use a single layer instead of a two-layer structure. It also discusses the simplification of the soil structure approach depending on the reflection coefficient. It introduces the reflection coefficient K interval which determines if single layer approach is acceptable. Multiple case studies are presented to address the new approach and its accuracy

Keywords: Earth grid; High voltage substation; Reflection coefficient, Soil resistivity.

1. Introduction
High voltage infrastructure requires earthing design to warrant the safety and meet the relevant standards and regulations. Earthing system presents a safe working environment for workers and people passing by during a fault or malfunction of the power system. Soil resistivity structure is one of the main elements that impacts - the design. The change in the soil resistivity structure can result in a complex earthing design [1]. The soil body consists of layers; which could be horizontal or vertical. These layers consist of variable thicknesses which differ from the parent materials in their texture, structure, content, color, chemical, biological, and other physical characteristics [2].
This paper presents a new approach as to when it is acceptable to use a single layer soil structure for the earth grid determination. It also simplifies the apparent soil resistivity formula to represent the two layers depending on the reflection coefficient, thus providing a novel method for quick assessment with two-layer soil structure. A case study is conducted and the results are presented.

2. Theoretical study
Soil resistivity is a measure of a soil's ability to retard the conduction of an electric current. Soil resistivity values typically range from about 2 to 100000 Ω.m, yet more extreme values are not unusual.
Table 1 shows the different types of soil and their typical soil resistivities. In practical cases, soil can be represented by two layers; it is rare to find a single layer structure [3].
As the mass of earth plays part in any electrical infrastructure and plays an important role in absorbing the fault and malfunction energy of these plants. Soil resistivity structure is the key in this operation and determination of the soil resistivity will establish the conductivity of the ground which determines its

capability to form an easy path for the fault. The resistance R depends on the resistivity of the medium as shown in equation 1:

$$R = \frac{\rho \times L}{A} \tag{1}$$

where: ρ is the resistivity of the conductor ($\Omega.m$), L is the length of the conductor (m), A is the cross section area (m^2)

Table1. Typical soil resistivities of various types of soil

Type of Soil or water	Typical Resistivity ($\Omega.m$)
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

Figure 1 shows the apparent resistivity of 5 types of two layers soil structures. The electrode separation S can have the value between 0 and infinite, the apparent soil resistivity can have the value between 2 and 100 $k\Omega.m$ depend on the soil ground. This figure gives an indicative understanding on the soil structure using the field test data

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

Soil resistivity field test can be performed using the following methods [4, 5].

- Wenner Method
- Schlumberger Array
- Driven Rod Method

The soil structure can be computed using the field test data. It is important to achieve a soil model that represents the existing soil structure or close to ensure that a rigid system will be established based on this computed structure. According to IEEE 80, two layers soil resistivity structure (SRS) are often a good approximation of many soil structures. This computation can be achieved manually or by using computer aided software.

The two-layer structure consists of the characteristics shown in Table 2,

Dealing with a two-layer soil structure to determine the grid resistance, introduces the reflection coefficient K. Equation 2 shows the computation of the reflection coefficient K. Depending on the soil structure type, K could have a negative or positive value.

$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \tag{2}$$

where: ρ_2 is the bottom layer soil resistivity, ρ_1 is the top layer soil resistivity.

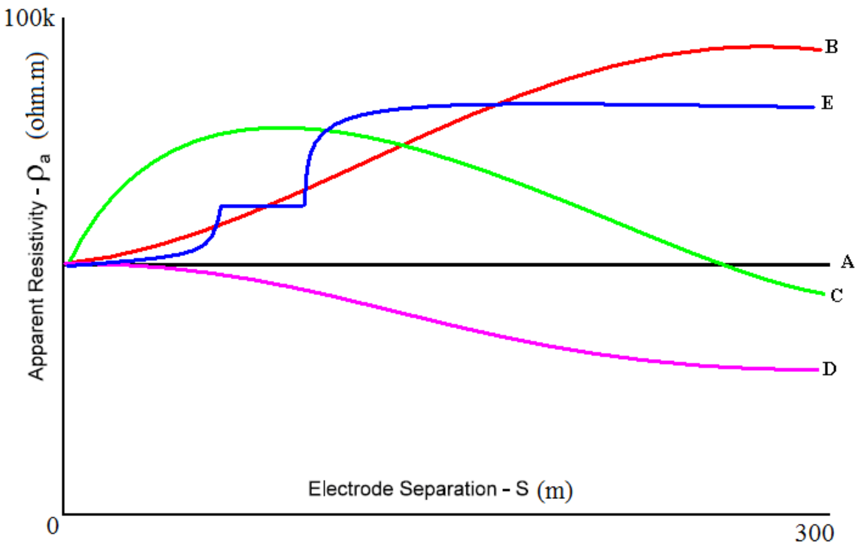

Figure 1. Two layers soil structure layout

Table 2. Two-layer soil resistivity

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

Where H is the depth of the top soil layer.

The reflection coefficient K plays a vital role in computing an apparent soil resistivity to reflect that two layers characteristics can be used in Schwarz equations [1]. For a negative reflection coefficient K, equation 3 is derived to represent the apparent soil resistivity for the two- layer structure [6, 7].

$$\rho_a = \frac{\rho_1}{\left(1+\left(\frac{1-K}{1+K}-1\right)\times\left(1-e^{\frac{-1}{-k(d+2h)}}\right)\right)} \quad (3)$$

For a positive reflection coefficient K, equation 4 is derived to represent the apparent soil resistivity for the two- layer structure.

$$\rho_a = \rho_2\left(1+\left(\frac{1+K}{1-K}-1\right)\times\left(1-e^{\frac{-1}{k(d+2h)}}\right)\right) \quad (4)$$

where: d is the depth of the top layer, h is the grid depth.

The calculated apparent soil resistivity will be used in equation 5 when determining the grid resistance

$$R_g = \rho_a\left[\frac{1}{L_T}+\frac{1}{\sqrt{20A}}\left(1+\frac{1}{1+h\sqrt{\frac{20}{A}}}\right)\right] \quad (5)$$

where: L_T is the total length of the grid conductor (m), A is the area occupied by the grid (m^2), h is the depth of the buried grid (m)

For a negative reflection coefficient, the analysis shows that equation 6 stands and can be considered as a good approximation for the soil structure when the reflection coefficient is approaching the zero value

$$\underset{K\to[f]}{Limit}(\rho_a)\approx\rho_2 \tag{6}$$

where: f is a constant between 0 and 1.

Equation 7 can be derived by substituting equation 6 into equation 3:

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

Equation 8 is derived from equations 7 and 2:

$$1+\left(\frac{1-K}{1+K}-1\right)\times\left(1-e^{\frac{-1}{-k(d+2h)}}\right)\approx\frac{1-K}{1+K} \tag{8}$$

Equation 8 is correct only when K is approaching zero value. The presented analysis shows that for K between [-0.2 - 0], the apparent soil resistivity can have the value of the second layer resistivity.
For a positive reflection coefficient, the equation 9 stands and can be considered as a good approximation for the soil structure when the reflection coefficient is approaching zero.

$$\underset{K\to[f]}{Limit}(\rho_a)\approx\frac{\rho_2^2}{\rho_1} \tag{9}$$

$$\frac{\rho_2^2}{\rho_1}=\rho_2\left(1+\left(\frac{1+K}{1-K}-1\right)\times\left(1-e^{\frac{-1}{k(d+2h)}}\right)\right) \tag{10}$$

Equation 11 is derived by analyzing equations 10 and 2:

$$e^{\frac{-1}{k(d+2h)}}\times\left(1-\frac{1+K}{1-K}\right)=0 \tag{11}$$

Equations 10 and 11 are valid only when K is approaching zero. The analysis shows that for K between [0-0.2], the apparent resistance can have the value as given by equation 9.
To apply this approach, the maximum positive K shall be 0.2, which means $\rho_2=1.5\rho_1$ and for the negative K, $\rho_1=1.5\rho_2$.

3. Case studies

A new 132kV zone substation is required to support the electrical load for a new development of 3500 houses in Sydney. The proposed substation takes into account future growth and allows for 5 distribution transformers. The design inputs are as follows:

- Area occupied is 100 by 100 metres
- Single line to fault current is 10,000 amperes
- Primary clearance time is 500ms
- Five proposed locations for new substations

Five locations have been chosen for the new substation. The soil resistivities tests using Wenner method are performed at each location. Table 3 represents the field test data. Initial observation of the data, using the soil structure layout as per Figure 1, provides the following information:

- SRS at location 1 consists of low resistivity layer overlaying high resistivity layer
- SRS at location 2 consists of high resistivity layer overlaying a low resistivity layer
- SRS at location 3 consists of low resistance layer overlaying high resistivity layer
- SRS at location 4 consists of low resistance layer overlaying high resistivity layer
- SRS at location 5 consists of low resistance layer overlaying high resistivity layer

Table 3. Field data used for case study

Probe S (m)	Location #1 ($\Omega.m$)	Location #2 ($\Omega.m$)	Location #3 ($\Omega.m$)	Location #4 ($\Omega.m$)	Location #5 ($\Omega.m$)
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

The software, Current Distribution, Electromagnetic Field, Ground and Soil Structure Analysis (CDEGS), is used to compute the soil structure based on the tested field data as per Table 3. The results are shown in Table 4. These values comply with the initial observation as per Figure 1.
Applying equation 2 to determine the reflection coefficient and shown in Table 5.

Table 4. Two-layer soil structure for field tests

Number of Layers	Location #1 Resistivity ($\Omega.m$)	Location #2 Resistivity ($\Omega.m$)	Location #3 Resistivity ($\Omega.m$)	Location #4 Resistivity ($\Omega.m$)	Location #5 Resistivity ($\Omega.m$)
1	25	716	10	36	35
2	156	221	42	48	215

Table 5. Reflection coefficient

Case Study	Location #1	Location #2	Location #3	Location #4	Location #5
K	0.72	-0.52	0.61	0.14	0.72

For soil structure at location #4, the reflection coefficient is 0.14 which meets 0.2 maximum requirements. The reflection coefficient is positive and applying equation 9, the apparent soil resistivity is:

$$\left(\rho_a\right) \approx \frac{\rho_2^2}{\rho_1} = \frac{48^2}{36} = 64\Omega.m$$

Applying average soil resistivity for soil structure locations #1 and 2 [8-10], the apparent soil resistivity is computed to be:

$$\rho_{a-1} = 51\Omega.m \qquad \rho_{a-2} = 603\Omega.m$$

Figure 2 shows the proposed substation earth grid with the mesh grid and the electrodes system.

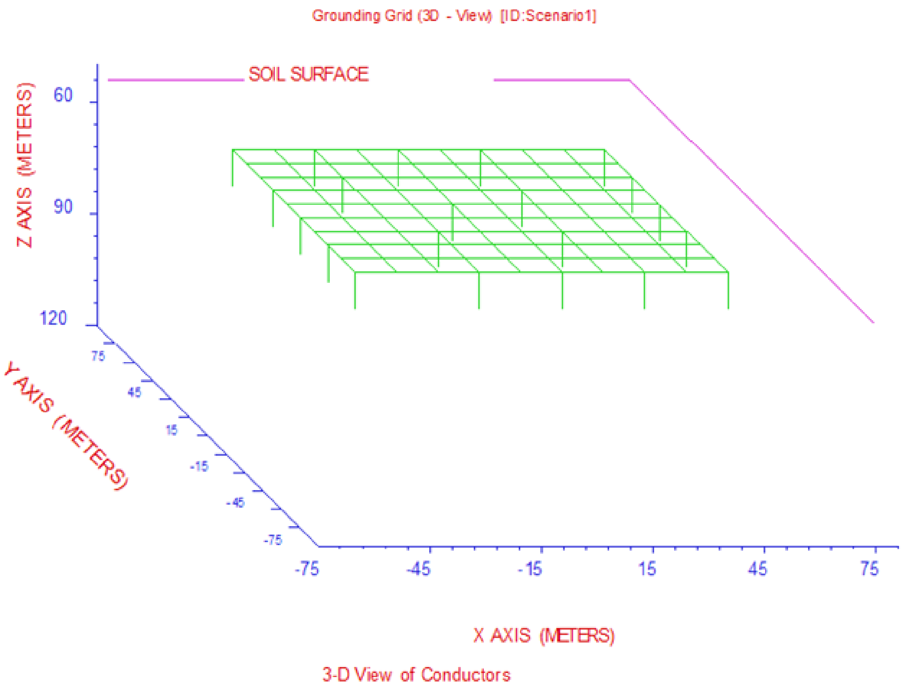

Figure 2. Earth grid layout

CDEGS software is used to compute the earth grid resistance for the proposed earth grid using the two soil layers at location #4, the results are shown below:

$$R_{grid} = 0.21\Omega$$

Running the simulation with the apparent soil resistivity computed with proposed approach, the grid resistance is computed to be:

$$R_{grid} = 0.27\Omega$$

The difference is 0.06 Ω

A second simulation is completed using the soil structure at location #1, the grid resistance is computed to be:

$$R_{grid} = 0.5\Omega$$

The grid resistance under apparent soil estimation for location #1 is computed to be:

$$R_{grid} = 0.22\Omega$$

A third simulation is completed using the soil structure at location #2; the grid resistance is computed to be:

$$R_{grid} = 1.2\Omega$$

The grid resistance under apparent soil estimation for location #2 is computed to be:

$$R_{grid} = 2.69\Omega$$

From the above grid resistance computations, it is shown the large change in the grid resistance at locations 1 & 2 when applying single layer soil structure approach. For location 4 where the reflection coefficient lies within the [-0.2–0.2], both two and single layers yield similar results. Therefore, it is clear that for a reflection coefficient situated outside the interval [-0.2-0.2], the computation of the earth grid will not yield similar results between single and two layers soil resistivity. Figure 3 shows the earth potential rise computation for the substation under the soil resistivity at locations #1, 2 & 4. It is clearly shown that at location #4 computations yields similar results between the two layers and single layer approach.

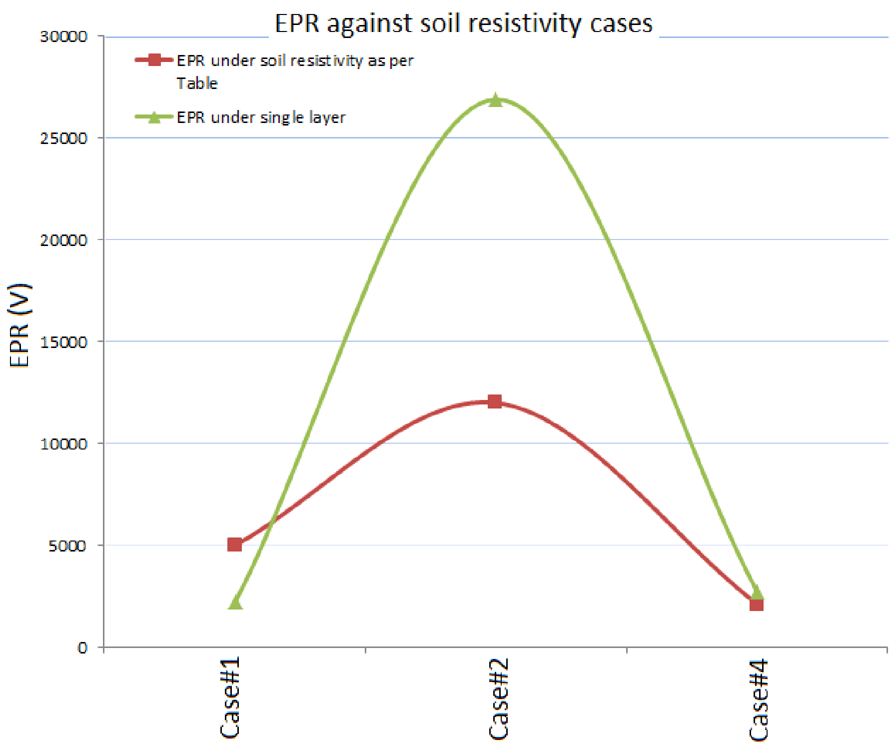

Figure 3. Substation EPR against soil resistivity cases

4. Conclusion

This paper highlights the importance between single and two layers soil resistivity structures. It introduced the reflection coefficient interval which aids in determining when it is acceptable to use an estimated apparent soil resistivity approach. Furthermore, the acceptance of single layer approach allows for the use of simplified formulas during the earthing system design. The case study showed that by studying the reflection coefficient of the soil structure, it is possible to make a decision if single layer approach is acceptable. The estimated apparent soil resistivity under this paper yield similar results to the two layers approach if the reflection coefficient situated within the interval [-0.2 – 0.2]

Acknowledgment

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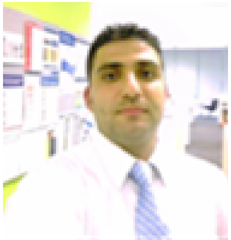

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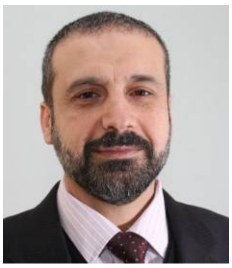

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