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Assessment of the Grid Safety Values for Substation Grounding Grid Design Parameters in Vertical Two-Layer Soil Structure

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ABSTRACT

Typically, the impact of the structure of vertically layered soil on the grounding behavior is not considered while designing a substation grounding system. Therefore, it will result in poor grounding designs due to computed inaccurate grid safety values. Besides, no comparative analysis of the grounding design parameters' impact on the grounding grid systems' behavior and protection level between vertical and horizontal two-layer soil structures is presently available. Computing and analyzing the grounding behavior of apparent soil resistivity installed in a vertical two-layer soil structure is more challenging than in a horizontal two-layer soil. There are many other parameters to consider, such as the distance 'a' between the test electrodes and the angle 'β' between the perpendicular line to the soil boundary and the location of the test electrodes. One of the important findings of the assessment shows that the influence of vertically layered soil on grid impedance, step, and touch voltages of a grounding system is insignificant compared to a homogeneous and horizontally layered soil structure. The current flow is affected by an entire grounding grid placed in a specified layer of soil with a specific resistivity for horizontally layered soil. In contrast, soil boundaries separate a grounding grid with various resistivities for vertically layered soil. The outcome of this work is crucial in helping the engineers to understand the behavior of grounding systems in diverse soil conditions and tropical climates.

Keywords: Grounding behavior, horizontal soil layers, substation, tropical climate, vertical soil layers

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INTRODUCTION

The soil characteristics in which the grid will be buried must be reviewed and evaluated when planning an efficient and safe grounding grid system. The substation grounding grid configuration is vital in ensuring the grounding system's safety, which is highly dependent on the soil characteristics in which the grounding system will be installed (IEEE 80, 2013; Gursu & Cevdet, 2019; Moradi, 2020; Nikolovski et al., 2016; Pavel et al., 2020; Sing et al., 2013; Vyas & Jamnani, 2012). Soil resistivity varies greatly depending on the earth's geological structure (Coelho et al., 2018; Nassereddine et al., 2010; Ma & Dawalibi, 2009; Tung & Lim, 2017; Vycital et al., 2017; Yang & Zou, 2020). Due to the variations in soil conditions at each substation, the grounding system design is made with caution to provide the maximum level of protection. Vertical and horizontal soil layers influence the installation site for the grounding system. For example, a grid located in a vertically layered soil structure might have a different safety level than one positioned in a horizontally layered soil structure. When a grounding system is designed based on vertically-layered soil, the grounding system's performance is governed by the proportion of grounding systems in low- and high-resistivity soils. In contrast, if a grounding grid ought to be built in a horizontally layered soil structure, the height and soil resistivity of the top layer will impact the performance of a grounding system as a whole (Mokhtari et al., 2016b; Nahman & Paunovic, 2006; Takahashi & Kawase, 1990). Despite knowing that the soil characteristics in which a grounding grid is installed are non-homogeneous in general, the soil is frequently considered homogeneous due to the challenges of grounding systems assessment in non-homogeneous soil. Thus, the calculation of ground resistance and surface potentials will be inaccurate due to this assumption.

Most substation grounding system safety evaluations and design procedures employ a homogenous soil environment as an input to calculate safety values (grid impedance, step, and touch voltages). However, despite significant studies into grounding behavior in homogenous soil environments (Mokhtari et al., 2016a; Nikolovski et al., 2016; Pavel et al., 2020) and horizontal two-layer soil with varying soil properties such as the upper layer height (Zaini & Ghoneim, 2012) and the soil reflection factors (K) (Gouda et al., 2019; Tong et al., 2019) and varying grid design parameters such as the analysis of single horizontal grounding conductor (de Araujo et al., 2019; Arnautovski-Toseva et al., 2007), the mesh count of a grounding system (Unde & Kushare, 2012), vertical rod length (Anggoro et al., 2018), there is presently no comprehensive study available that assess the grounding behavior in vertical two-layer soil under the impact of design parameters. Furthermore, no simultaneous comparisons or discussions between horizontal and vertical two-layer soil structures are available. The desired study would show the difference in behavior and protection levels of a grounding system when placed in different soil structures and if existing grounding system design procedures are appropriate for designing a grounding grid installed in vertically stratified soil.

Figure 1 depicts the vertical soil structure, while Equation 1 depicts its apparent resistivity. The first-layer soil resistivity is represented as ρ_1 (Ωm), the soil resistivity of the second layer is shown as ρ_2 (Ωm), the distance between 4 electrodes is represented as 'a' (m), K is the reflection factor between soil layer 1 and 2, the normal distance between the first electrode and boundary between soil layers 1 and 2 is represented as 'd' and 'β' is the angle between the straight line where 4 electrodes are located and perpendicular line to the boundary between soil layer 1 and 2. The varying electrode spacing 'a', the distance from the two-layer soil interface 'd' and the angle 'β' between a perpendicular line to the soil border and the line where 4 electrodes are positioned have different effects on the apparent resistivity which have been presented in Nayel (2014) and Nayel et al. (2012).

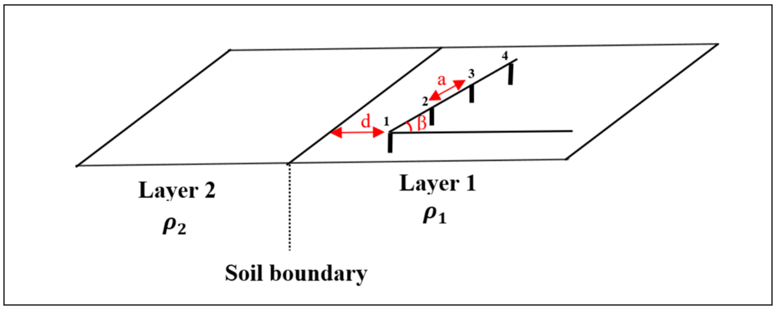


Figure 1. Vertical two-layer soil structure

$$\rho_a = a\rho_1\left(\frac{1}{a} + \frac{K}{\sqrt{4d^2+4da\cos\beta+a^2}} + \frac{K}{\sqrt{4(d+3a\cos\beta)(d+2a\cos\beta)+a^2}} - \frac{K}{\sqrt{4d^2+8da\cos\beta+4a^2}} - \frac{K}{\sqrt{4(d+3a\cos\beta)(d+a\cos\beta)+4a^2}}\right) \quad [1]$$

Where

ρ_1 = Layer 1/right-layer soil resistivity (Ω.m)

ρ_2 = Layer 2/left-layer soil resistivity (Ω.m)

K = reflection factor between soil layers 1 and 2

a = distance between 4 electrodes Wenner's test (m)

d = the normal distance between the first electrode and boundary between soil layers 1 and 2

β = angle between line where 4 electrodes are located and perpendicular line to the boundary between soil layers 1 and 2.

A detailed discussion on the impact of the soil resistivity in vertically-layered soil on the grounding behavior will be given in the Results and Discussions section. The low soil resistivity is assumed to be 100 Ω.m on layer 2 and 1000 Ω.m for high resistivity on layer 1 of the soil structure.

INPUT PARAMETERS AND METHODOLOGY

Design Parameters for Substation Grounding Grids

An analysis of grounding grid performance for different grid designs was conducted at a power frequency response of 50 Hz with a centrally energized fault current of 30 kA, as shown in Figure 2. The fault current is maintained constant in the middle of the grid because the maximal Ground Potential Rise (GPR) and grounding resistance at the current injection location at the grid's center are significantly lower than at the grounding grid's periphery. The inductance of grounding conductors will prevent the fault current from dispersing in other directions if the fault current is injected into a corner. However, the grounding conductors will be effective for a modest inductive effect when the current injection location is in the middle. Figure 2 shows the methodology of the grounding design analysis process.

The grounding behavior analysis was conducted using grid sizes ranging from 30 m × 30 m to 130 m × 130 m. The dimensions chosen for the grounding grid are based on assumptions intended for research purposes, but the fundamental grid size is based on the Tenaga Nasional Berhad substation. The grounding grid size is based on a 132/33/11 kV Main Intake Substation as specified in the Tenaga Nasional Berhad Substation Design Manual (Asset Management Department, 2012; TNB, 2019), which was throughout the analysis apart from the analysis on the grid sizes. Then, the analysis was continued by varying the mesh sizes from 5 m × 5 m to 21.7 m × 21.7 m. A 130 m × 130 m grounding grid with a mesh size of 10 m × 10 m is shown in Figure 2. The mesh size of 5 m × 5 m is made up of equally spaced 27 horizontal and 27 vertical grid conductors; a 10 m × 10

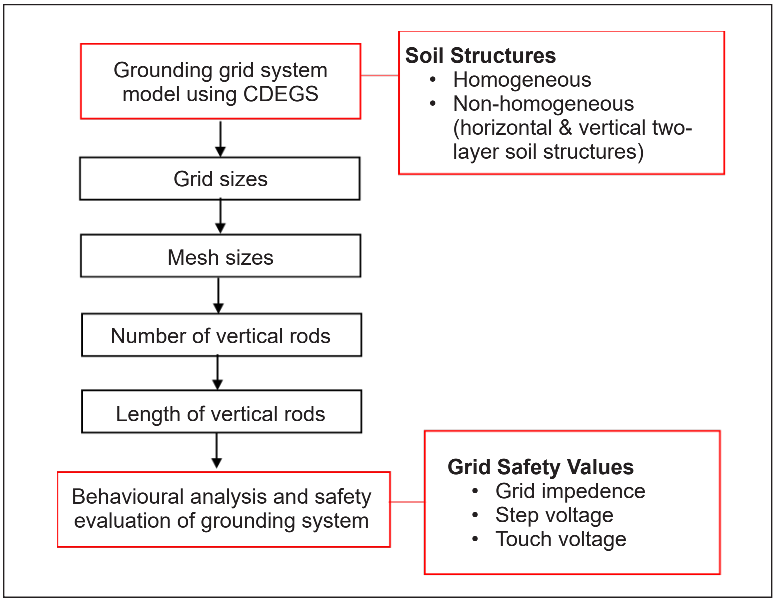


Figure 2. Methodology of grounding system design analysis

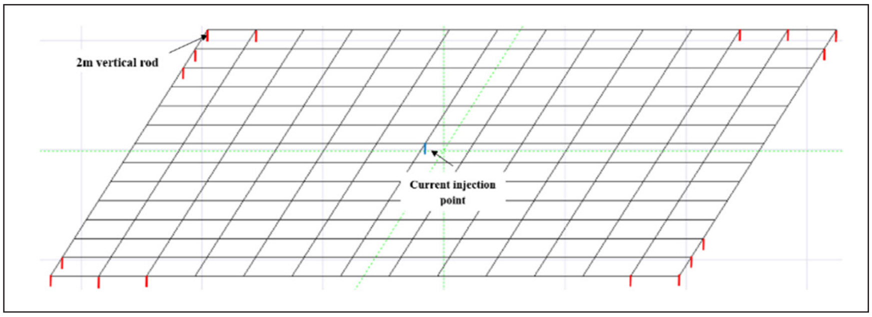


Figure 3. The grounding grid comprises 16 vertical rods attached

m has 14 horizontal and 14 vertical grid conductors; a 16.3 m × 16.3 m has 9 horizontal and 9 vertical grid conductors while mesh size of 21.7 m × 21.7 m has 7 horizontal and 7 vertical grid conductors.

The analysis is followed by varying the number of vertical rods from 4 rods to 16 rods. At the grid's perimeter, the vertical rods connecting to the grid conductors are varied from 4 to 16 rods once the grounding mesh size analysis is completed. The rods are placed on the grid's perimeter throughout the analysis because most fault current is discharged through the bottom section of vertical rods, making them efficient in controlling the high current densities that occur in grounding conductors at the perimeter. In addition, due to the increasing shielding effect between both grounding conductors and vertical rods when the vertical rods are positioned in the middle of the grid, the impact of the potential gradient of the vertical rod placed on the grid's perimeter has less influence than the rod placed in the middle. Figure 3 shows 16 rods placed at the grounding grid's perimeter. Each rod is 2 meters in length.

The analysis of the different lengths of vertical rods was then continued. The vertical rod helps in discharging more current into the earth than the grid conductor for a given length of grid conductor. The lengths of 4 rods placed at the grounding grid's edges range from 2 to 6 meters. The summary of the grounding design process with grids buried 0.5 m into the soil is shown in Table 1. Each design is classified into different case numbers.

Table 1
Analysis of grounding design parameters with constant grid depth at 0.5 m

Design Parameters	Case number
Grounding grid size	
30 m × 30 m	A1
50 m × 50 m	A2
130 m × 130 m	A3
Grounding mesh size	
5 m × 5 m	B1
10 m × 10 m	B2
16.3 m × 16.3 m	B3
21.7 m × 21.7 m	B4
Number of electrodes	
4 rods	C1
8 rods	C2
13 rods	C3
16 rods	C4
Length of electrodes	
2 m	D1
4 m	D2
6 m	D3

Computation of Soil Boundary in Vertical Soil Structure

The proportions of the grounding grid in a vertically layered soil utilized in CDEGS simulation are shown in Figure 4. The percentage of soil ratio (%) indicates the proportions of the grounding grid placed on the soil border's left side (layer 2) compared to the right side (layer 1). The soil ratios are ranged between 25%, 50 %, and 75%. The soil ratio of 25% refers to the location of the majority of the grounding grid in high resistivity soil, with just 25% of the grounding grid in low resistivity soil. A 50% soil ratio means that the soil resistivity on both layers 1 and 2 of the grounding grid is equal; with low resistivity (layer 2) and high resistivity (layer 1), and a 75% soil ratio means that most of the grid on the right is located in low resistivity soil. The Trace Angle (θ), between the soil boundary with the positive direction of the x-axis of the coordinate system, is assumed at 90°.

The grounding system's performance and safety level computation in the vertical soil layer is not straightforward compared to the horizontal soil layer. Since grounding behavior is modeled and analyzed in CDEGS, three main parameters, as indicated in Figure 5 (red box), must be addressed: the Trace Angle (θ), X Reference, and Y Reference. The test electrodes in the vertical soil layer are assumed to parallel the vertical soil boundary. Therefore, the Trace Angle (θ) in CDEGS computation and the 'β' value from the vertical soil layer Equation 1 is presumed to be similar.

The X and Y References, which define the soil boundary in the vertical soil model, require some computations depending on the grounding grid dimensions, as in Figure 6.

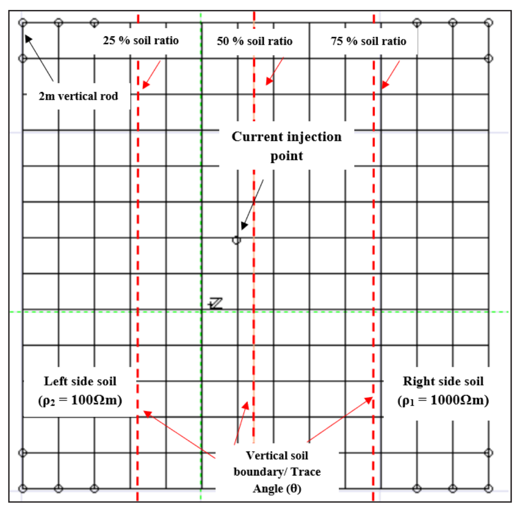


Figure 5. Vertical soil model in CDEGS

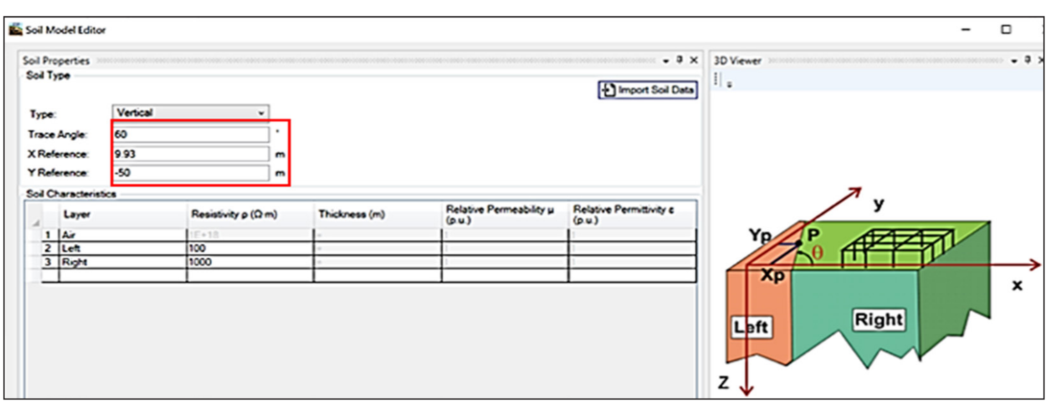


Figure 4. The proportion of grounding grid in vertically layered soil

The dark red letters represent the known quantities (given by the user): (I) c and d are the edges of the grounding grid, (II) k is the ratio of the left area (S1) to the right area (S2) and (III) θ is the Trace Angle assuming the grounding grid is parallel to the x-axis. Again, there are two equations, Equations 2 and 3, with two unknowns.

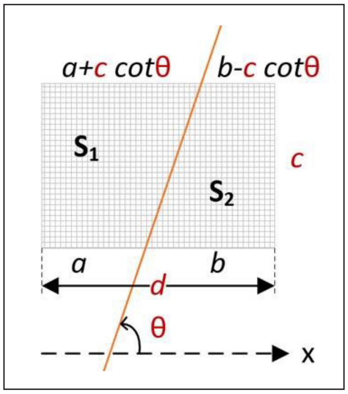


Figure 6. Soil proportion of two-layer vertical soil

$$S_1 = \frac{1}{2} \times \ (2a + c\ cot\theta) \times \ c \qquad [2]$$

$$S_2 = \frac{1}{2} \times \ (2b - c\ cot\theta) \times c \qquad [3]$$

$$\mathrm{a} + \mathrm{b} = \mathrm{d} \qquad [4]$$

$$\frac{\mathrm{S_1}}{\mathrm{S_2}} = \mathrm{k} \qquad [5]$$

Putting the Equations 4 and 5 in matrix form:

$$\begin{bmatrix} 1 & 1 \\ 2 & -2\mathrm{k} \end{bmatrix} \begin{bmatrix} \mathrm{a} \\ \mathrm{b} \end{bmatrix} = \begin{bmatrix} \mathrm{d} \\ -\mathrm{c} \times \cot\theta \times (1 + \mathrm{k}) \end{bmatrix} \qquad [6]$$

Where
θ = Trace Angle (°)
‘c’ and ‘d’ = edges of the grid (m)
S_1 = left area (m^2)
S_2 = right area (m^2)
‘k’ = ratio of the left area to the right area

The ratio of ‘k’ is 25/75 for 25 % soil ratio, 50/50 for 50 % soil ratio, and 75/25 for 75 % soil ratio in this paper. By solving the 2 by 2 system from Equation 6 for the Trace Angle, θ, the ratio of the left area to the right area ‘k’ and edges of the grid ‘c’ and ‘d’, one of the points belonging to the boundary line by solving ‘a’ or ‘b’ is (X Reference, Y Reference) = (-50 + a, -50) m. The coordinate of the bottom-left corner of the grid is (-50, -50). Then, the x-coordinate is shifted by adding ‘a’.

RESULTS AND DISCUSSIONS

Comparison of Percentage Difference in Grid Impedance in Different Soil Structures for Various Design Parameters

This section represents the percentage difference in grid impedance for various design parameters of grounding, such as the sizes of grounding grids, the mesh sizes of a grid, the length and number of vertical rods in a grounding system placed in different soil structures. Since there are many results in analyzing the grounding behavior, only a few examples were presented in this study. An example of the percentage difference calculation in grid impedance of 30 m × 30 m grid size, which is placed in low resistive homogeneous soil and low resistive upper layer of horizontal two-layer soil structure, is shown in Table 2. For the horizontal two-layer soil model, the top layer soil with the resistivity of 1000 Ω.m and the lower layer resistivity of 100 Ω.m with infinite depth is denoted as Top (1000 Ω.m), while the top layer soil with the resistivity of 100 Ω.m and the lower layer resistivity of 1000 Ω.m with infinite depth is denoted as Top (100 Ω.m). The top layer thickness of a horizontal two-layer soil structure is 5 m.

Table 2
Grid impedance for grounding design parameters in homogeneous and horizontal two-layer soil structure

Grid size	Homogeneous soil		Horizontal two-layer soil	
	Uni (100 Ωm)	Uni (1000 Ωm)	Top (100 Ωm)	Top (1000 Ωm)
30 m × 30 m	**1.66 Ω**	16.55 Ω	**5.33 Ω**	7.82 Ω
50 m × 50 m	0.96 Ω	9.60 Ω	3.92 Ω	3.51 Ω
130 m × 130 m	0.35 Ω	3.52 Ω	2.06 Ω	0.80 Ω

$$\text{Grid impedance percentage difference (\%)} = [|1.66\ \Omega - 5.33\ \Omega| / (5.33\ \Omega)] \times 100 = 68.95\ \%$$

Figure 7 presents the percentage difference in grid impedance when a grid is positioned in a low resistive homogenous soil (Uni (100 Ωm)) and high resistive homogenous soil (Uni (1000 Ωm)), and vertical two-layer soil structure with various soil ratios (25%, 50%, and 75%).

Figure 8 presents the percentage difference in impedance when the grid is positioned in a low resistive top soil layer of a horizontal two-layer soil structure, denoted as Top (100 Ωm), and the high resistive top soil layer denoted as Top (1000 Ωm), and vertical two-layer soil structures with different soil ratios.

Figures 7 and 8 demonstrate that the impedance value for different soil conditions varies significantly. It indicates the potential for errors if the soil structure of which a grounding grid will be installed is presumed as homogeneous. Figure 9 shows the impedances differences for varied vertical rods lengths placed in various soil structures. The findings demonstrate that the length of vertical rods has a major impact on the performance of a grounding system, especially in horizontally layered soil. The vertical rods of 2 m and 4 m are located before the soil border, while the 6 m vertical rods have passed through the soil boundary with different soil resistivity from the top soil layer's resistivity, which is absent in homogenous and vertical two-layer soil structure. As a result, when compared to homogenous and vertically layered soil structures, a significant difference can be seen, particularly for 6 m vertical rods at the high resistive bottom layer.

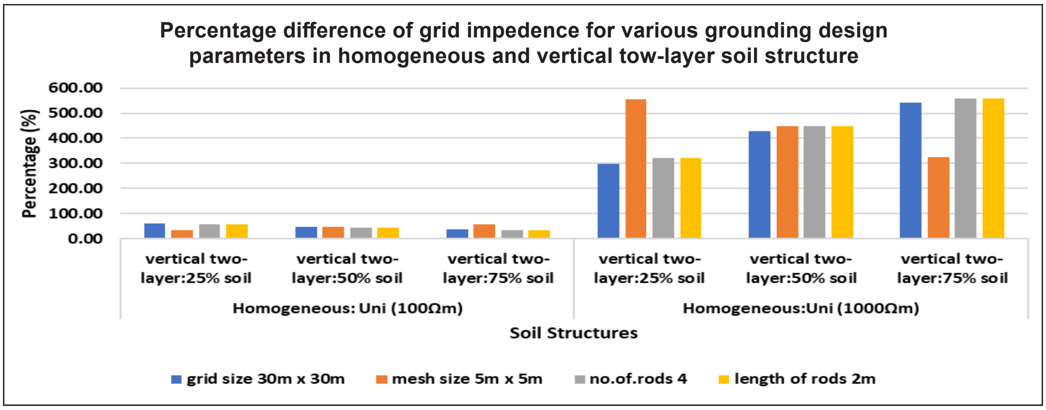


Figure 7. Percentage difference of grid impedance for grounding design parameters in homogeneous and vertical two-layer soil structure

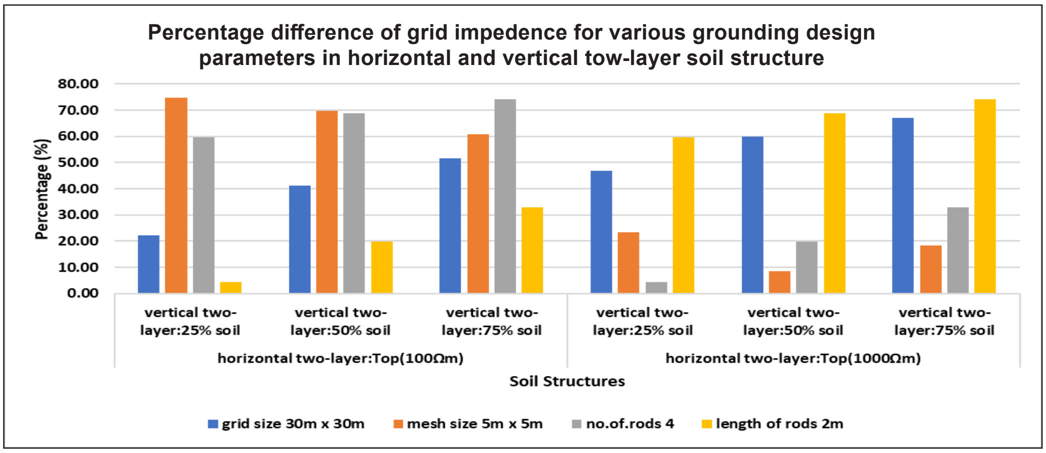


Figure 8. Percentage difference of grid impedance for grounding design parameters in horizontal and vertical two-layer soil structure

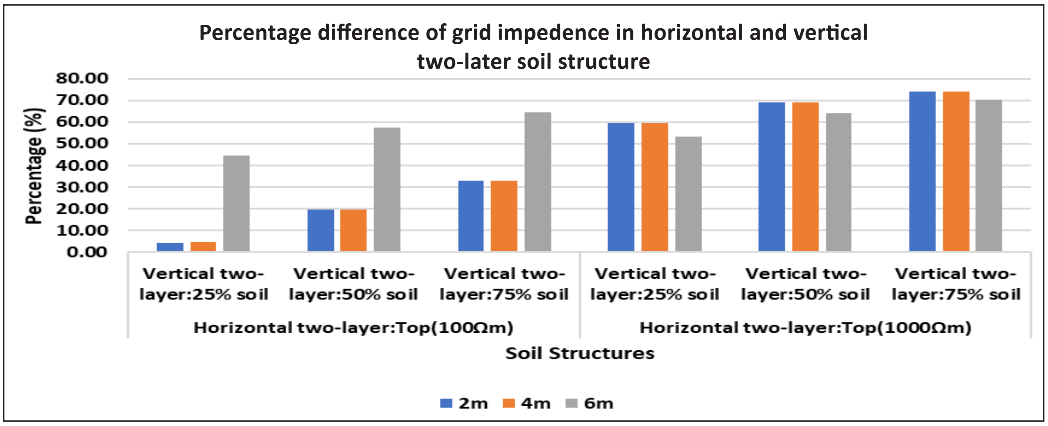
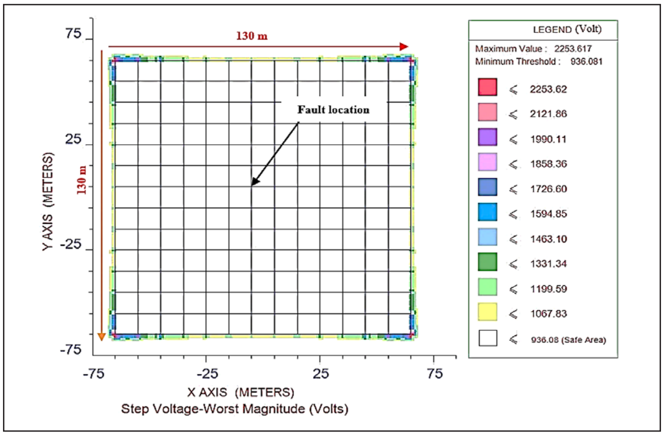


Figure 9. Percentage difference of grid impedance for different vertical rod lengths in horizontal and vertical two-layer soil structure

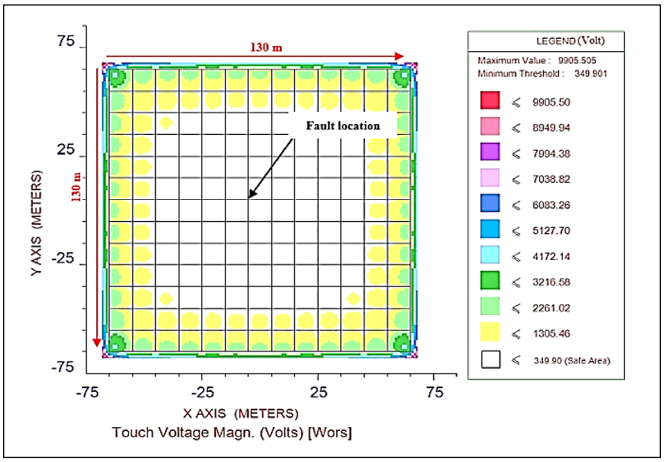
Grounding Behavior in Vertical Two-Layer Soil: Effects of Grid Design Parameters

Based on horizontal two-layer soil data given in Permal et al. (2021), comparisons of grounding behavior between vertical and horizontal two-layer soil structures are presented. The safety threshold for vertically layered two-layer soil is 1120 V and 399.2 V for step and touch voltage correspondingly for all soil ratios (25%, 50%, and 75%) calculated based on equations available in IEEE 80 (2013) for a bodyweight of 50 kg. According to IEEE 80 (2013) and the Malaysian Utility standard (Asset Management Department, 2012), the grid impedance threshold value is 1 Ω.

Figures 10(a) and 10(b) illustrate the examples of step and touch voltages using Current Distribution, Electromagnetic Fields, Grounding, and Soil Structure Analysis (CDEGS) simulation software as reported by Permal et al. (2021) for the horizontal two-layer soil model. Figures 10(a) and 10(b) illustrate that the highest voltages are found to be at the



(a)



(b)

Figure 10. Grounding grid safety voltages for a 130 m × 130 m grid. (a) step voltage (b) touch voltage (Permal et al., 2021)

edges of the profile boundaries of the grounding grid. The propagations of fault current injected into the grid to the nearby conductors result in this condition. Being bare, the conductors will allow the current to leak into the soil. By doing so, the conductors will acquire a potential rise. The current dispersion between the middle and corner grounding conductors is significantly different, resulting in a substantially greater step and voltage at the edges than in the middle of the grid (He et al., 2013). A grounding grid is regarded as reliable and protected in this study if all the values of grid impedance, step, and touch voltages fall under the safety threshold mentioned before.

The Number of Vertical Rods. This section examines the effect of varying numbers of vertical rods placed on a 130 m × 130 m grounding grid with a 10 m × 10 m mesh size. Two meters of a varying number of vertical rods are positioned around the grid's periphery. The graphs of grid impedance, step, and touch voltage reduction percentages as the number of vertical rods rise from 4 to 16 in various soil ratios are shown in Figures 11 to 13. When the rods are added, safety values' magnitudes reduce for all soil ratios, similar to grounding behavior in different mesh sizes.

The percentage of impedance reduction in Figure 11 as the vertical rods increases from 4 rods to 16 rods (C1 to C4) is around 0.31% for grounding placed in 25%, 0.56% for 50% soil ratio, and 0.78% for 75% soil ratios. Compared to the horizontal two-layer soil, the overall impedance percentage reduction is much lower in the vertical soil layer when vertical rods are added (less than 1%). In contrast, the step voltage reduction in horizontal two-layer soil is reduced by about 21%, as seen in Figure 14. Similar to grid sizes, this may be attributable to the impact of two different soil resistivities on a grounding grid in the vertical soil layer, while an entire grounding grid in the horizontal soil layer is influenced by a top soil layer with a specific resistivity.

For step voltages in Figure 12, the reduction percentage as the vertical rods increases from 4 rods to 16 rods (C1 to C4) is the highest at 75% soil ratio and lowest at 25% ratio with 5.0 % and 2.8% of reduction, respectively. For touch voltage in Figure 13, the reduction percentage as vertical rods increases from 4 rods to 16 rods (C1 to C4) is 3.7% for 75% soil ratio, 2.5% for 50% soil ratio, and 1.5% for 25% soil ratio.

As previously stated, the number of vertical rods differs depending on the soil ratios. Therefore, increasing the number of rods by adding 8 rods on the left of the grid on low resistive soil, as shown in Figure 15, helps lower the grid impedance. For example, adding the number of rods (adding 8 rods, a total of 16 vertical rods) on layer 1 (low resistive soil) for a 25% soil ratio, while at layer 2, the number of rods remains 8 rods, helps in reducing the grid impedance further by dissipating more current into the soil.

The percentage of impedance reduction in Figure 16 shows that although most of the grid is placed in a high resistivity soil, a significant reduction from the initial total of 16

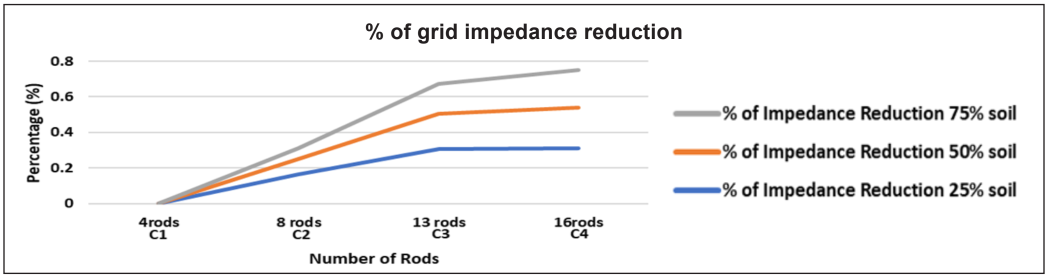


Figure 11. Percentage of grid impedance reduction for an increasing number of vertical rods in the vertical soil layer

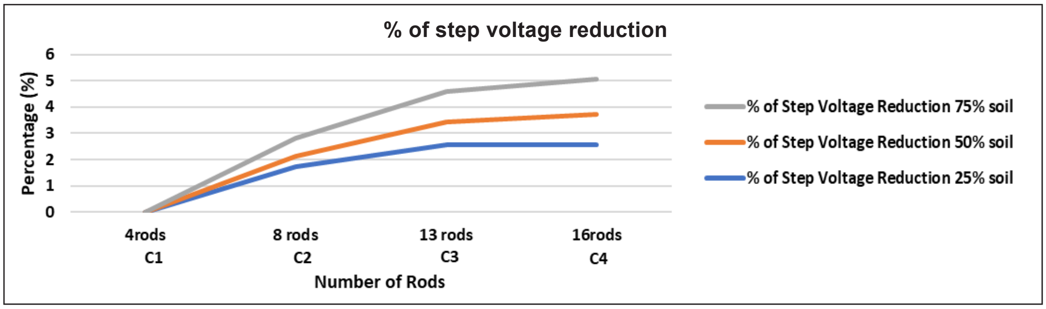


Figure 12. Percentage of step voltage reduction for an increasing number of vertical rods in the vertical soil layer

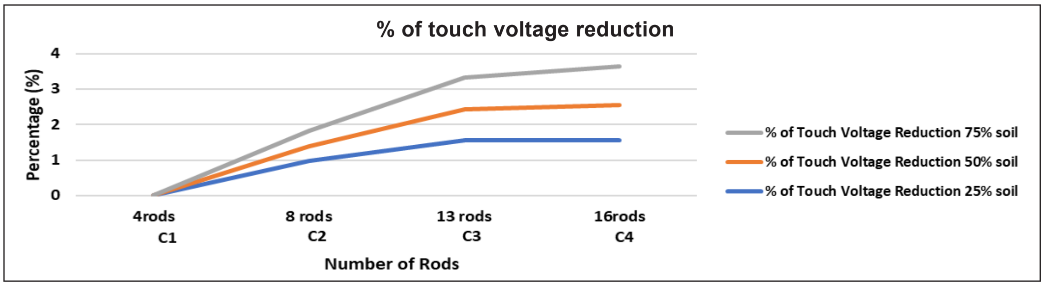


Figure 13. Percentage of touch voltage reduction for an increasing number of vertical rods in the vertical soil layer

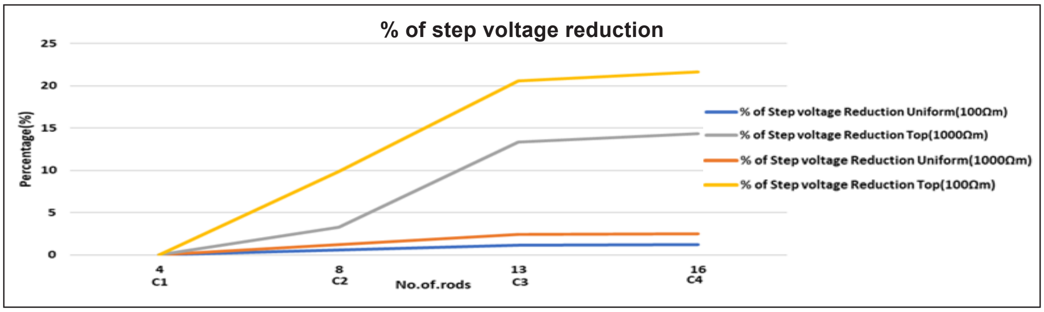


Figure 14. Percentage reduction for step voltage as the number of vertical rods rises in horizontal two-layer soil (Permal et al., 2021)

rods can be seen by adding 8 rods to the low resistivity soil in a 25% soil ratio compared to 50% and 75% soil ratio. It demonstrates that adding more vertical rods in low resistive soil would help in reducing the grid impedance.

Given that the magnitudes of the safety parameters (impedance, step, and touch voltages) drop as the number of vertical rods rises, a grounding system must have a sufficient number of vertical rods to enhance the safety of a grounding system. For example, Table 3 shows that a grounding system with 16 vertical rods is not safe in all vertical two-layer soil structure soil ratios. However, an additional 8 rods on layer 1, which is on the low resistive soil layer, helped enhance the grounding system's safety. Although Figure 16 shows that the percentage of impedance reduction is the highest for grounding placed in a 25% soil ratio, however, it is not sufficient to improve the grounding's safety compared to a 75% soil ratio.

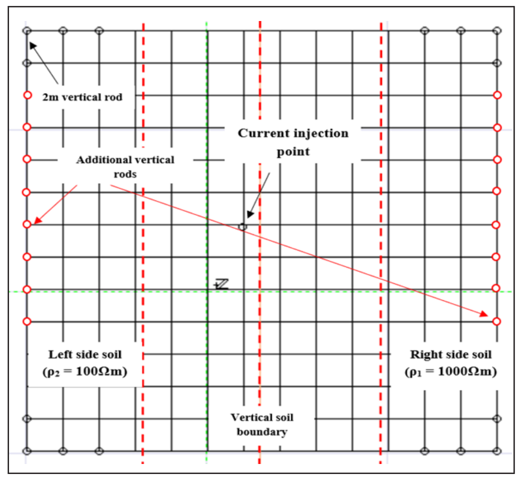


Figure 15. Illustrations of the additional number of rods on layer 1 and layer 2 of vertically layered soil

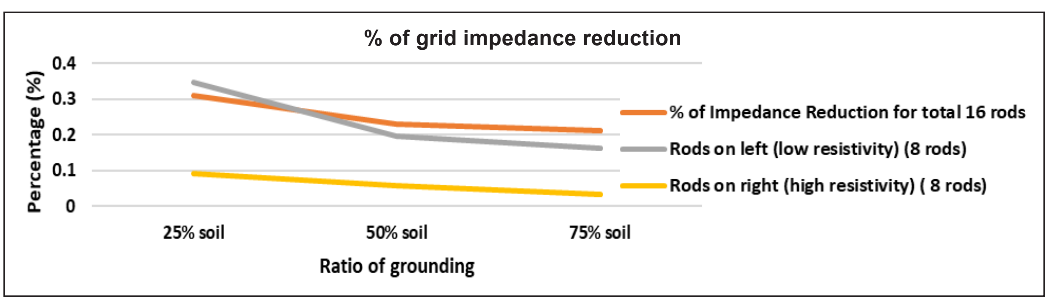


Figure 16. Percentage of grid impedance reduction for adding more vertical rods to the main grounding grid in the vertical soil layer

Table 3
A grounding system's safety assessment for the varying number of vertical rods

Number of vertical rods	The ratio of vertical two-layer soil		
	25 % soil	50 % soil	75 % soil
4 rods	Unsafe	Unsafe	Unsafe
8 rods	Unsafe	Unsafe	Unsafe
13 rods	Unsafe	Unsafe	Unsafe
16 rods	Unsafe	Unsafe	Unsafe
8 rods (left)	Unsafe	Unsafe	Safe
8 rods (right)	Unsafe	Unsafe	Unsafe

Length of Vertical Rods. This section investigates the effect of the varying length of four vertical rods placed on a 130 m × 130 m grounding grid with a mesh size of 10 m × 10 m. Figures 17 to 19 depict a graph of grid impedance, step, and contact voltage reduction percentages as the length of vertical rods increases from 2 m to 6 m in various soil ratios. Similar to the number of rods, the magnitudes of safety parameters in the vertical soil layer continue to lower for all soil ratios when the length of rods is increased. This behavior contrasts with the grounding grid behavior in a horizontally layered soil structure. As

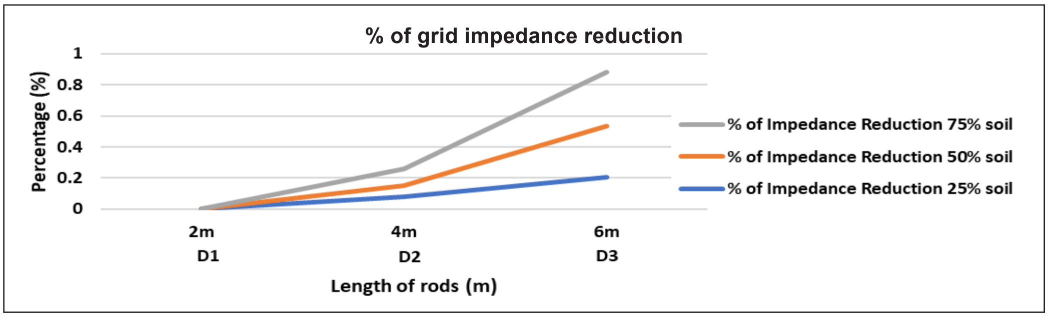


Figure 17. Percentage of grid impedance reduction for increasing length of 4 vertical rods in the vertical soil layer

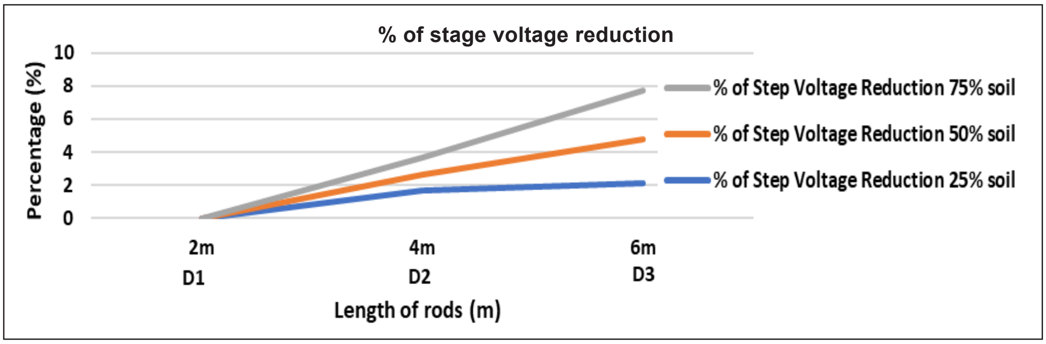


Figure 18. Percentage of step voltage reduction for increasing length of 4 vertical rods in the vertical soil layer

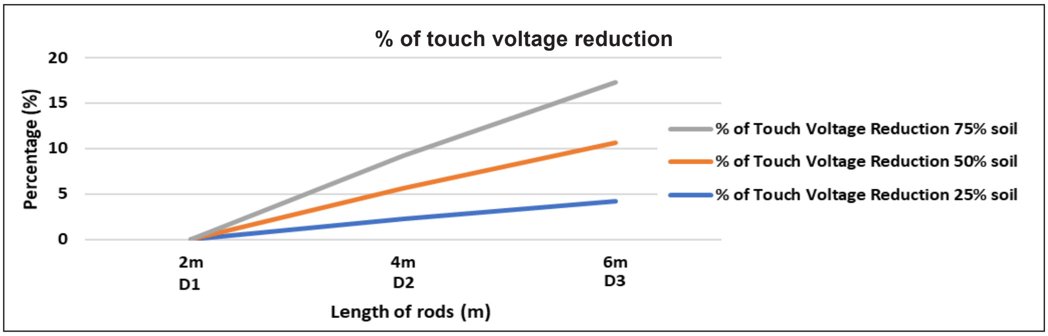


Figure 19. Percentage of touch voltage reduction for increasing length of 4 vertical rods in the vertical soil layer

illustrated in Figure 20, grid impedance may increase when the vertical rods cross beyond the two-layer soil border with a high resistive bottom layer for a low resistive top layer of the horizontal two-layer soil.

The percentage of impedance reduction in Figure 17 as the length of vertical rods increases from 2 m to 6 m (D1 to D3) is around 0.13% for grounding placed in 25% soil ratio, and 0.38% for 50% soil ratio, and 0.63% for 75% soil ratios.

For step voltages in Figure 18, the percentage of reduction as the length of vertical rods increases from 2 m to 6 m (D1 to D3) is the highest at 75% soil ratio and lowest at 25% ratio with 7.84% and 2.24% of reduction respectively. For the 75% soil ratio, most of the grid is placed in a low resistive soil layer, allowing more current to disperse into the soil and lowering the safety parameters, and vice versa for the grid placed in the 25% soil ratio.

For touch voltage in Figure 19, the highest percentage of reduction as the length of vertical rods increases from 2 m to 6 m (D1 to D3) can be seen at 16.09% for a 75% soil ratio and the lowest at around 3.66% of reduction for 25% soil ratios.

Similar to the number of rods, the magnitudes of safety parameters in the vertical soil layer continue to lower for all soil ratios when the length of rods is increased. This behavior is similar to grounding behavior in homogeneous soil but in contrast to the grounding grid behavior in a horizontally layered soil structure. For horizontal two-layer soil with a low resistive top layer, as illustrated in Figure 20, there is an increase in grid impedance, step, and touch voltages when the length of rods passes through a soil boundary with a high resistive bottom soil layer.

The difference in behavior between horizontal and vertical two-layer soil structures is caused by the effect of two distinct soil resistivity on each vertical rod in the horizontal soil layer. In contrast, a single soil layer influences every vertical rod in the vertical soil layer with a specific resistivity (either left or right). Therefore, adding the length of vertical rods as shown in Figure 21 (adding 8 m, 14 m length of each vertical rod) on layer 2 for low resistive soil in 25% soil ratio, and each rod length on layer 1 remains at 6 m, helps in reducing the grid impedance further, as shown in Figure 22.

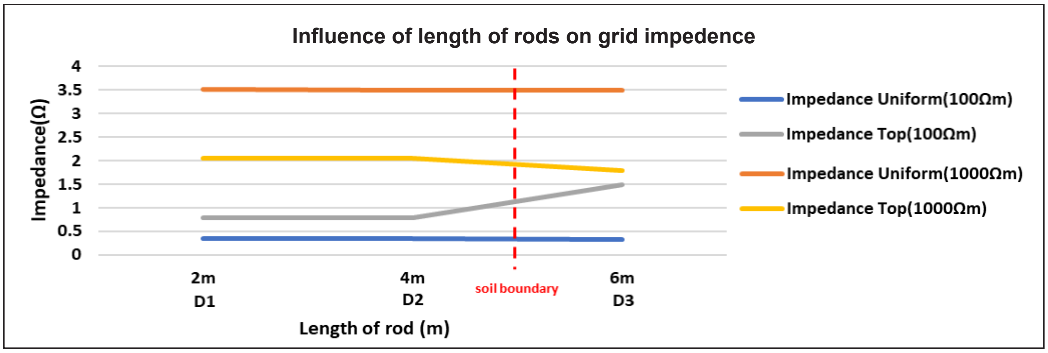


Figure 20. Grid impedance graph for increasing vertical rod length in horizontal two-layer soil (Permal et al., 2021)

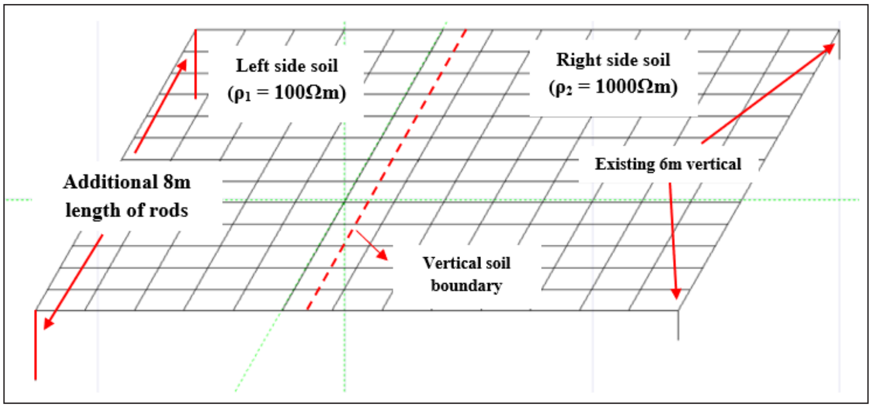


Figure 21. Illustrations of the additional length of rods on layer 2 and layer 1 of vertically layered soil

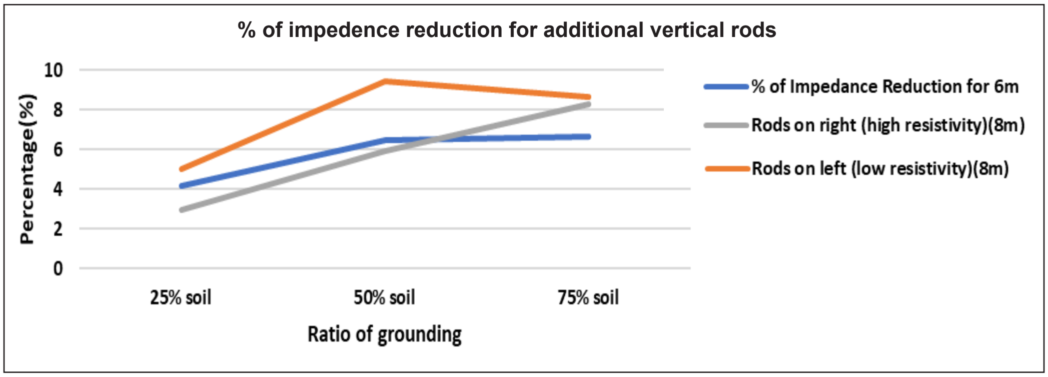


Figure 22. Percentage of grid impedance reduction for extending the length of vertical rods to the primary grounding grid in the vertical soil layer

Longer rods are only effective in less resistive soil layers. Therefore, more current will spread over a longer rod, reducing the grid safety values and securing the grounding system, as shown in Table 4. Increasing the length of rods on low-resistance soil also helps to dissipate more current into the soil, lowering grounding grid impedance in all soil ratios. Thus, it is important to make a vertical rod sufficiently long to disperse more current

Table 4
A grounding system's safety assessment for different vertical rods' lengths

Length of rods	**The ratio of vertical two-layer soil**		
	25 % soil	50 %	75 %
2 m	Unsafe	Unsafe	Unsafe
4 m	Unsafe	Unsafe	Unsafe
6 m	Unsafe	Unsafe	Unsafe
8 m (left)	Unsafe	Unsafe	Safe
8 m (right)	Unsafe	Unsafe	Unsafe

through a longer rod and help enhance the grid's safety. However, it can also be seen that the grounding system is still not safe even when the length of vertical rods is added in the 25% and 50% soil ratio. It can be resolved by further increasing the length of rods or adding more numbers of vertical rods on the low resistive soil layer.

Grounding Grid Size. The magnitudes of impedance, touch, and step voltage for various grid sizes in varied soil ratios of vertically layered soil are presented. The grid impedance, step, and touch voltages in Figures 23 to 25 show that all groundings behave the same way, decreasing magnitudes as the grid size expands. The results show that the grid safety parameters (impedance, step, and touch voltage) in 25%, 50%, and 75% soil ratios of vertical two-layer soil are higher than a high resistive top layer of horizontal two-layer soil. It is because the current density at the grid's perimeter is high, which is caused by the flow of the current outward from a high resistive soil layer. On the other hand, the grid safety parameters are lower in vertical two-layer soil than in a high resistive top layer of horizontal two-layer soil because of the current dispersion into the lower resistivity layer.

Figure 23 shows the impedance reduction of 61% from 50 m × 50 m to 130 m × 130 m grid size (A2 and A3) in a 75% soil ratio of a vertical two-layer soil is lower compared to the percentage of impedance reduction of 77% of the same grounding grid placed in a horizontal soil layer with a high soil resistivity top layer as can be seen for grid impedance in Figure 26 (Permal et al., 2021). The difference in the percentage of impedance reduction in horizontal and vertical two-layer soil shows that the soil structure impacts the grounding system's behavior. For horizontally layered soil, an entire grounding grid is positioned in a specific layer with a specific resistivity (normally the first layer of soil). A grounding grid is divided by a soil boundary with different resistivities for vertically two-layered soil.

Figure 24 shows that the step reduction percentage from 50 m × 50 m to 130 m × 130 m grid size (A2 and A3) in a 75% soil ratio is higher than grid placed in 25% and 50% soil ratios of a vertical two-layer soil. Figure 25 shows the touch reduction percentage of

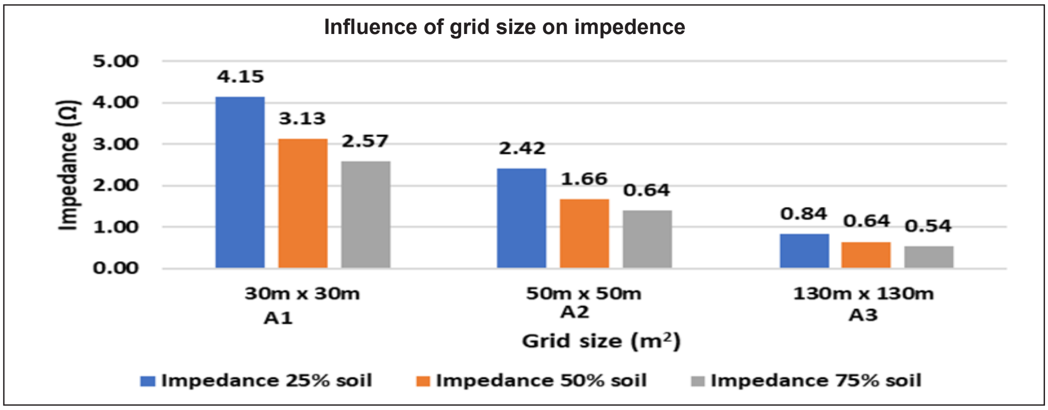


Figure 23. Grid impedance in the vertical soil layer for increasing grid size

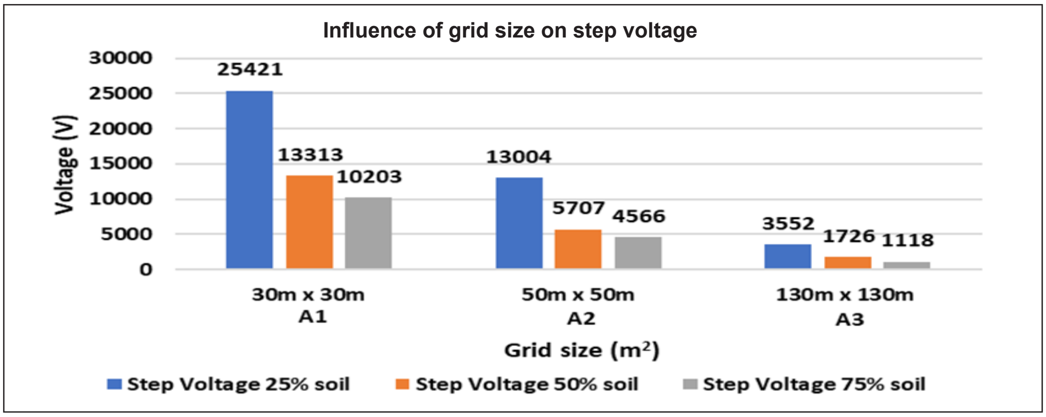


Figure 24. Step voltages in the vertical soil layer for increasing grid size

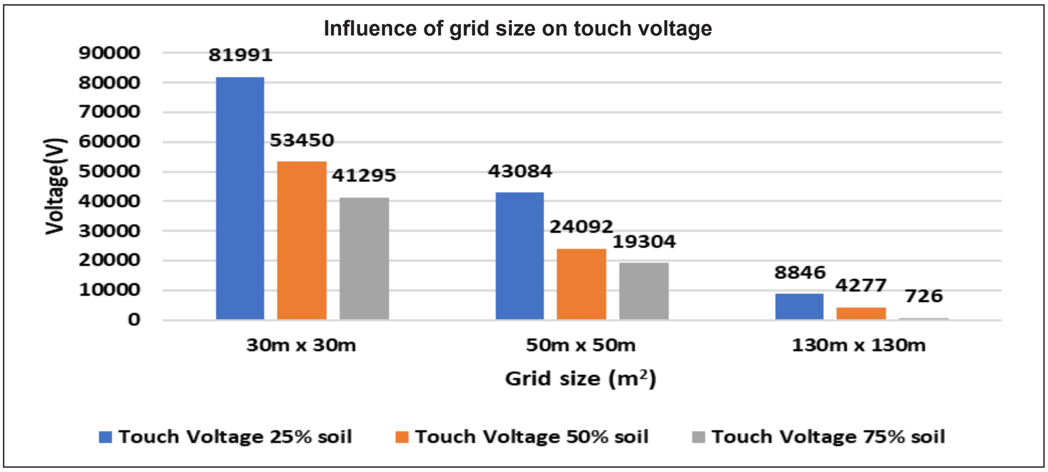


Figure 25. Touch voltages in the vertical soil layer for increasing grid size

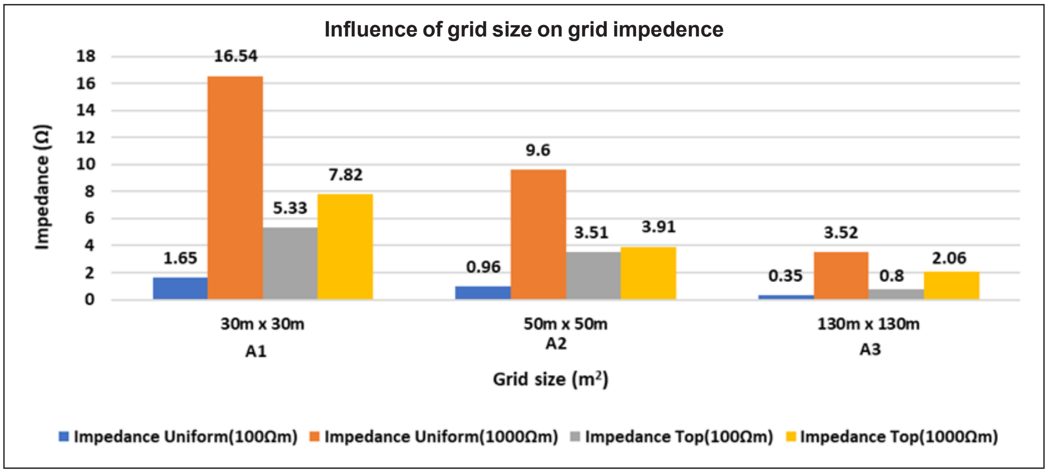


Figure 26. Grid impedance for increasing grid sizes in horizontal two-layer soil (Permal et al., 2021)

Table 5
A grounding system's safety assessment for varied grid sizes

Grid size	The ratio of vertical two-layer soil		
	25 % soil	50 % soil	75 % soil
30 m × 30 m	Unsafe	Unsafe	Unsafe
50 m × 50 m	Unsafe	Unsafe	Unsafe
130 m × 130 m	Unsafe	Unsafe	Unsafe

47% from 50 m × 50 m to 130 m × 130 m grid size (A2 and A3) in a 75% soil ratio of a vertical two-layer soil.

When placed in a vertical soil structure with varied soil ratios, the grounding grid's size affects its behavior and safety. As known, a grounding system must be large enough to keep the impedance and safety voltages (step and touch) within the allowable limit. Even when a substantial portion of a grounding grid is placed in a low resistive, vertically layered two-layer structure, a large grid does not ensure safety. Table 5 illustrates the grounding system's overall safety evaluation, which meets all three acceptable levels (impedance, step, and touch voltages). When placed in varied soil ratios, it can be observed that all three grid sizes are unsafe. Further adjustments such as decreasing the mesh size or connecting vertical rods to the primary grounding grid are necessary to produce a safe grounding grid.

Grounding Mesh Size. The impact of varying mesh sizes of a 130 m × 130 m grounding grid will be discussed in this part. Figures 27 to 29 demonstrate a similar behavior pattern for varying mesh sizes to grounding behavior in varying grid sizes. Figure 30 shows how the impedance, touch, and step voltage increase as the mesh size increases in horizontally layered soil. The percentage of impedance increment in Figure 27 as the mesh size increases from 5 m × 5 m to 16.3 m × 16.3 m (B1 to B3) is around 3.8 % for grounding placed in 25%, 4.2% for 50% soil ratio, and 4.7% for 75% soil ratios.

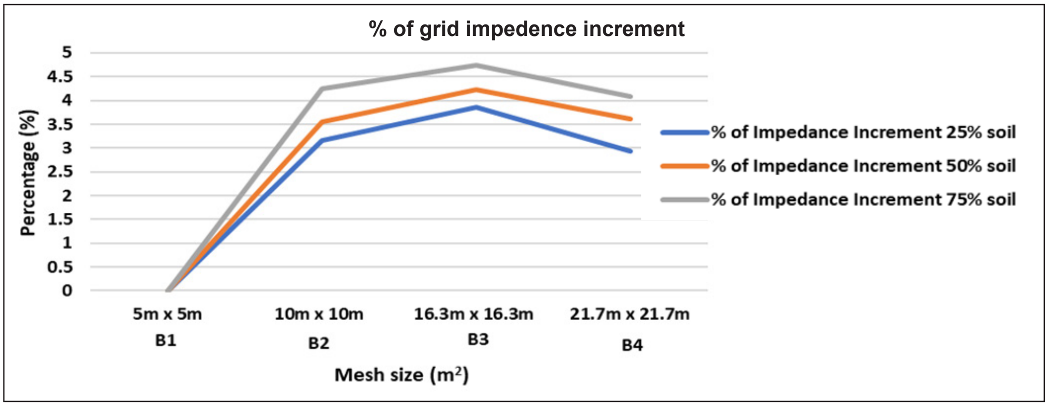


Figure 27. Percentage of grid impedance increment for increasing mesh sizes in the vertical soil layer

The percentage of step voltage increment in Figure 28 as the mesh size increases from 5 m × 5 m to 16.3 m × 16. 3 m (B1 to B3) is around 3.22% for grounding placed in 25%, 8.7% for 50% soil ratio, and 11.01% for 75% soil ratios.

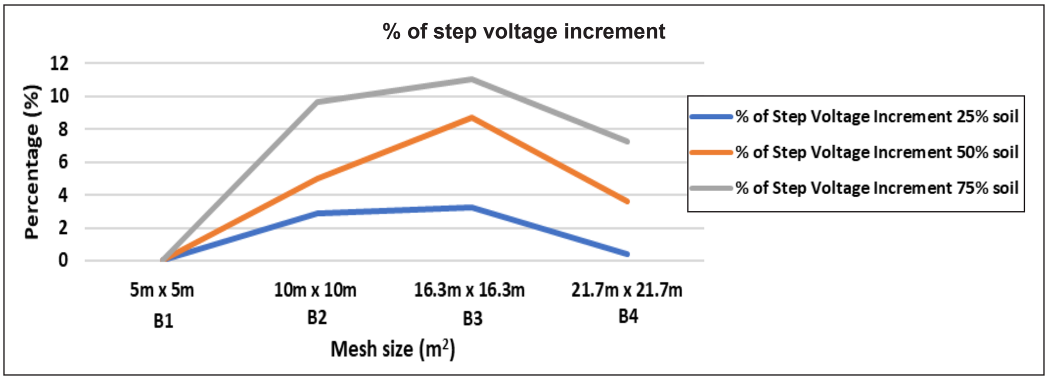


Figure 28. Percentage of step voltage increment for increasing mesh sizes in the vertical soil layer

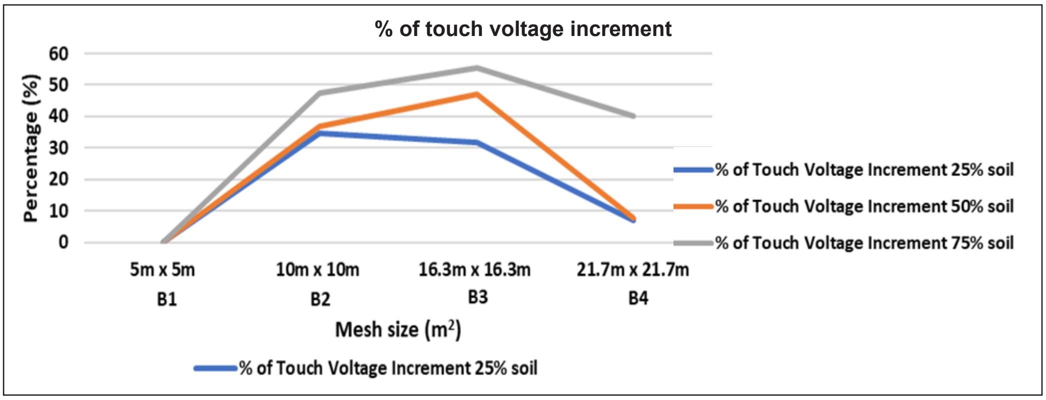


Figure 29. Percentage of touch voltage increment for increasing mesh sizes in the vertical soil layer

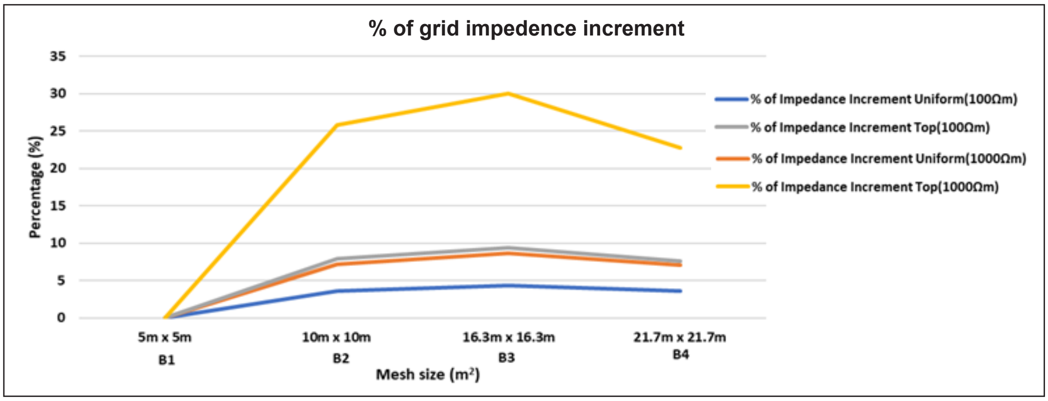


Figure 30. Percentage of grid impedance increment as mesh sizes increase in horizontal two-layer soil (Permal et al., 2021)

The percentage of touch voltage increment in Figure 29 as the mesh size increases from 5 m × 5 m to 16.3 m × 16.3 m (B1 to B3) is around 31.74% for grounding placed in 25%, 47% for 50% soil ratio, and 55.59% for 75% soil ratios.

Identical to grid size, the highest percentage of impedance, step, and touch voltages increment overall could be found for grounding in a 75% soil ratio. Conversely, the lowest increment percentage could be seen at a 25% soil ratio for increasing mesh sizes because of the proportion of the grid in different soil layers.

The percentage of grid impedance increment from 10 m × 10 m to 16.3 m × 16.3 m mesh sizes are small for all soil ratios and begins to drop at 16.3 m × 16.3 m mesh size, similar to horizontal two-layer. It indicates that the mesh size has attained its effective size. Varying the grid's mesh size has little influence on behavior when installed in soil structures with varying ratios of soil resistivity. However, it has an impact on the grounding's safety level.

Regardless of soil conditions with different resistivity values, the impedances for all analyzed mesh sizes are under the allowed value. Nevertheless, the step and touch voltages vary for every soil environment. For example, Table 6 indicates only a 130 m × 130 m grounding grid with a 5 m × 5 m mesh size is considered safe in 75% soil ratio but unsafe when placed in 25% and 50% soil ratios of a vertical two-layer soil. As a result, more changes are needed to ensure that the grounding is secure in all soil ratios.

Table 6
A grounding system's safety assessment for different mesh sizes

Mesh size	**The ratio of vertical two-layer soil**		
	25 % soil	50 % soil	75 % soil
5 m × 5 m	Unsafe	Unsafe	Safe
10 m × 10 m	Unsafe	Unsafe	Unsafe
16.3 m × 16.3 m	Unsafe	Unsafe	Unsafe
21.7 m × 21.7 m	Unsafe	Unsafe	Unsafe

The Effect of Surface Layer Resistivity on the Grounding Behavior. Figure 31 shows the influence of surface resistivity on the allowable step voltages in different soil ratios. The allowable step voltage is calculated using the IEEE 80 (2013) equation. Similar to homogeneous soil, the findings show that the allowable limits of safety voltages increase as surface resistivity increases. Without surface resistivity, step and touch voltage values will be lower. A comparison of allowable step voltage between high resistive and low resistive ρ1 is shown in Table 7. The allowable step voltage in vertical two-layer soil trailed the allowable step voltage in the high resistive homogeneous soil when the ρ_1 value at layer 1 of the vertical two-layer soil is highly resistive. This grounding behavior can be related to the influence of high soil resistivity, ρ_1 (1000 Ω.m), on layer 1 from the apparent soil resistivity in Equation 1.

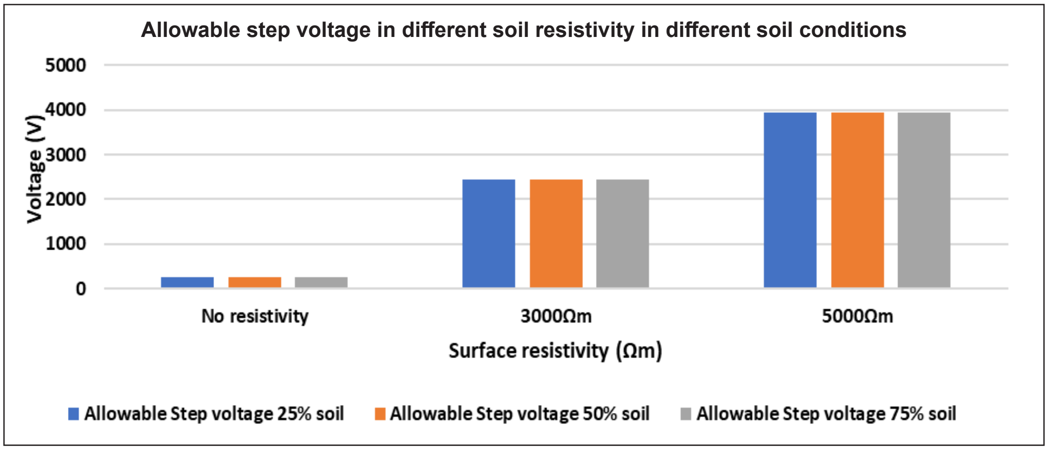


Figure 31. Allowable step and step and touch voltages for different soil ratios of vertical two-layer soil

Table 7
Comparison of ρ_1 value in vertical and horizontal two-layer soil on the allowable step voltage

	Allowable Step voltage (V)			
	Vertical	Homogeneous	Vertical	Homogeneous
Surface resistivity	Right soil (100Ω.m)	Uni (100Ω.m)	Right soil (1000Ω.m)	Uni (1000Ω.m)
1000Ω.m	936.1	936.1	1120	1120
3000Ω.m	2442	2442	2676	2676
5000Ω.m	3948	3948	4195	4195

The overall findings indicate that the effect of vertically layered soil on the reduction or increment of impedance, step, and touch voltages of the grid is small compared to horizontally layered soil. An entire grounding grid is installed in a particular layer of soil (usually the first soil layer) with a specific resistivity for horizontally layered soil. A grounding grid is divided by soil boundaries with different soil resistivities for vertically layered soil. Increasing the vertical rods' length has insignificant effects on the grounding behavior for vertical two-layer soil differs from the horizontal soil layer. Suppose the vertical rod is longer than the soil boundary. In that case, the current flow through two soil layers with different resistivity affects each vertical rod in the horizontal soil layer. In contrast, each vertical rod in the vertical soil layer is influenced by a single soil layer with a certain resistivity left or right.

In vertical two-layer soil, the grid safety values gradually reduce as the length of vertical rods increases. However, in horizontal two-layer soil, the safety values are governed by the height of the top soil layer and its corresponding soil resistivity. Besides, the location to place the number of vertical rods to be added in vertically layered soil structure is crucial compared to horizontally layered soil structure. For a horizontal two-layer soil, placing the vertical rods at any point on the grid's perimeter while increasing the number of vertical rods is acceptable. However, for a vertical two-layer soil structure, adding the number of vertical rods is recommended at the low resistive layer as it helps in reducing the grid impedance.

CONCLUSION

This study describes and compares the performance of the grounding system in varied design parameters placed in horizontal and vertical two-layer soil structures. According to the results, the grounding system's performance pattern in a vertical soil structure is identical to that of a horizontally layered soil structure as the grounding design parameters vary. However, as an overall comparison to the horizontal soil layer, the percentage of increase or decrease is much lower in the vertical soil layer because of the impact of two different soil resistivity as a grounding grid is divided by a soil boundary. Furthermore, in contrast to horizontally layered soil, installing a grounding grid in a vertical soil layer is more complicated because of the difficulty of the safety parameter computations required to design a safe grounding system.

In terms of grounding behavior, a noticeable increase/decrease can be seen more in the 75% soil ratio of the vertical soil layer, where most of the grid is located in a low resistivity soil layer. It indicates the importance of the grid's proportion placed in different soil layers. For the 75% soil ratio, most of the grid is placed in a low resistive soil layer, allowing more current to disperse into the soil and lowering the safety parameters, and vice versa for the grid placed in the 25% soil ratio.

The results also show that increasing the number of vertical rods in vertical two-layer soil has the smallest reduction percentages compared to the horizontal two-layer soil structures. The effect of vertically layered soil on the reduction or increment of grid impedance, step, and touch voltages of the grounding system is small compared to horizontally layered soil. For horizontally layered soil, an entire grounding grid is placed in a specific layer of soil (normally the top soil layer) with a specific resistivity. A grounding grid is divided by soil boundaries with different soil resistivities for vertically layered soil. Increasing the vertical rods' length has insignificant effects on the grounding behavior for vertical two-layer soil differs from the horizontal soil layer. Suppose the vertical rod is longer than the soil boundary. In that case, the current flow through soil layers with different resistivity affects each vertical rod in the horizontally layered soil. In contrast, each vertical rod in the vertically layered soil is influenced by a single soil layer with a certain resistivity on the left or right.

Thus, the magnitudes of safety parameters gradually reduce as the length of vertical rods increases in vertical two-layer soil. In contrast, the safety parameters are dependent on the soil resistivity and height of the top soil layer for horizontal two-layer soil. Therefore, increasing the number of vertical rods in vertically layered soil structures is crucial compared to horizontally layered soil structures. For a horizontal two-layer soil, placing the vertical rods at any point on the grid's perimeter with increasing the number of vertical rods is acceptable. However, for a vertical two-layer soil structure, an increase in the number of vertical rods is recommended at the low resistive layer as it helps in reducing the grid impedance significantly even if most of the grid is placed in a high resistive soil layer.

This work would add to the branch of knowledge by identifying and anticipating the behavior of the grounding system impacted by the design parameters in non-homogeneous soil conditions, more precisely on the vertical two-layer soil structure. Besides, comparing the grounding behavior between different soil conditions would help eliminate the misinterpretations of grounding behavior.

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