

RESEARCH ARTICLE

Feasibility and Safety Study of Grounding Design with Soil Resistivity Method in Penajam Area, East Kalimantan, Indonesia

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Abstract

As the need for electrical energy for various sectors increases, especially in Penajam, East Kalimantan, which is currently under construction of the Indonesian Capital City (IKN), the existence of a power plant is very necessary. The construction and development of power plants require special studies to ensure feasibility and safety. Grounding is one of the important aspects in an electrical system to distribute unwanted current errors into the ground. Grounding design in an electrical system requires several important data such as soil resistivity values, the number of rods used, and the area of the installation. These data are used as input to calculate the actual design potential value with the permissible potential tolerance value starting from Ground Potential Rise (GPR), mesh, step, and touch potential. The grounding installation area plan is carried out in an area of 2500 m² in the form of a square or rectangle with a sandy lithology with an average resistivity value of 42.25 Ωm and a clay area with an average value of 114.105 Ωm . Another plan is carried out using a grid design with 48 rods and without using rods. The rectangular sand area with a grid installation design using rods generally produces the smallest design potential value, namely a GPR value of 818.06 V, a mesh value of 83.85 V, and a step value of 80.38 V. The square clay area with a grid installation design without using rods generally produces the largest design potential value, namely a GPR value of 2262.98 V, a mesh value of 411.73 V, and a step value of 281.10 V. The main factor that most influences the determination of the grounding design potential value is the soil resistivity value and the lithology of the installation area as evidenced by the difference in the measured potential design value which is quite significant. However, the overall design plan in this study produces a safe and feasible conclusion as evidenced by all design value acquisitions being less than the tolerance limit set in the case of a human weight of 50 kg and 70 kg such as a step potential of 1798 – 2433.5 V and a touch potential of 572.5 – 774.49 V.

Keywords: Grounding, Resistivity, IKN

1. Introduction

Electricity is one of the important types of energy that is a primary need for mankind. Indonesian society, especially those in East Kalimantan with 4 million residents based on Indonesian Central Statistics Agency (BPS) data, utilizes electrical energy in various sectors such as infrastructure, agriculture, mining, industry, health, transportation, and others (Armansyah et al., 2024). The supply and demand for electrical energy, especially in East Kalimantan, will certainly increase over time, coupled with the development of the capital city of Indonesia, IKN (Sidik et al., 2023).

Power plants are one of the vital national objects/important infrastructure in Indonesia (Yulianto et al., 2022). With the construction and development of various types of power plants, it will support the national energy independence and resilience program (Nugroho et al., 2024). To support this program, a thorough study is needed. In the planning stage of the manufacture and development of power plants, studies need to be carried out, especially from the construction, economic, social, environmental, risk, and safety aspects (Abdel-Basset et al., 2021). One of the points that will intersect with all the aspects previously mentioned is regarding grounding in the electrical system.

Grounding in the electrical system can increase the level of security and safety and reduce the risk of electrical accidents. Grounding techniques are commonly used in homes, industries, or for other needs. The potential danger of electrical shock from fault currents can occur in normal electrical systems or from disturbances (abnormal) in the electrical system which can actually be minimized by grounding (Thabet & Mobarak, 2021). A grounding system that does not meet standards has the potential to cause negative impacts, ranging from potential damage to devices, electric shocks, to death (Table 1). Several important factors that influence the grounding design include the methods and materials used, the properties of the installation area, and various parameters of the design calculation value itself.

The main capital for calculating the grounding design is to know the resistivity value in the grounding installation area. To find out the resistivity value, it is necessary to carry out geoelectric measurements and interpretations using the Vertical Electrical Sounding (VES) technique which is usually carried out by geophysicists. The use of the Geoelectric method with the VES method is generally widely used for groundwater exploration (Lubang et al., 2023), mineral and coal exploration (Penna et al., 2024; Bharti et al., 2022), geotechnical studies (Sangprasat et al.,

2024), and the environment (Martinho, 2023). Specifically, it turns out that the output of the geoelectric method can be developed by electrical people for the purpose of assessing the feasibility test of the grounding design that has been designed.

Soil resistivity is a measure of the soil's ability to conduct electric current, which is an important parameter in the feasibility study of grounding system design. To ensure that the fault current can be effectively channeled to the earth (Gouda et al., 2023). Soil resistivity is influenced by several main factors, such as soil type and composition, humidity, temperature, and electrolyte solution content. The smaller the soil resistivity value, the better it is in grounding design (Putra et al., 2022).

Discussion of the resistivity value in this study as a study material in determining the design and location of safe and effective grounding. Soil resistivity data will be compared to its influence on the feasibility test of grounding design. In addition, researchers can calculate and conclude the mesh voltage, touch voltage, and step voltage values that can occur due to humans passing, approaching, or holding grounded facilities. These values must be within the tolerance limits that are considered safe (Dladla et al., 2022).

Table 1. The effect of electric current to human body (Sunarto dkk., 2022)

Electric Current (mA)	Effect on Human Body
0.0-0.9	No Reaction
0.9-1.2	Not cause seizures
1.2-1.6	Loss of Control
1.6-6.0	Begins to feel
6.0-8.0	Feel pins and needles in hands up to the elbows
8.0-13.0	Stiff in Hands
13.0-15.0	The pain is unbearable
15.0-20.0	Hard to release the conductor
20.0-50.0	Damage to human body
50.0-100.0	Probably cause death

2. Data and Methods

2.1 Soil Resistivity

The resistivity data in this study are the results of measurements in Penajam, East Kalimantan, which estimated travel time is approximately 1 hour using four-wheeled or two-wheeled vehicles from the IKN center. The measurement of 5 resistivity points was carried out by PT Soilens, which is the first geotechnical consulting company in Indonesia founded in 1971 offering soil investigation services and other engineering services. The results of the cross-section model obtained from the correlation between the 5 VES points are shown in Fig. 1. The distance between each VES point is approximately 500 – 600 m and the elevation is different so that the resulting cross-section model is corrected according to the elevation profile from VES point 1 to VES point 5.

PT. Soilens uses American Standard Testing and Materials (ASTM) D6431 on Standard Guide for Using the Direct Current Resistivity Method for Subsurface Site Characterization and ASTM G57 on Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method as a reference for standard operating procedure in conducting geoelectric measurements with the Wenner configuration. This method was chosen because it has the advantage of producing good signal readings with high noise reduction such as that

produced by fences, pipes, electric poles, and other conductive materials. The resistivity meter is used to record the apparent resistivity and voltage values of the soil layer. To produce the actual resistivity value as shown in Fig. 1, an inversion process must be carried out (Zein & Marshela, 2023).

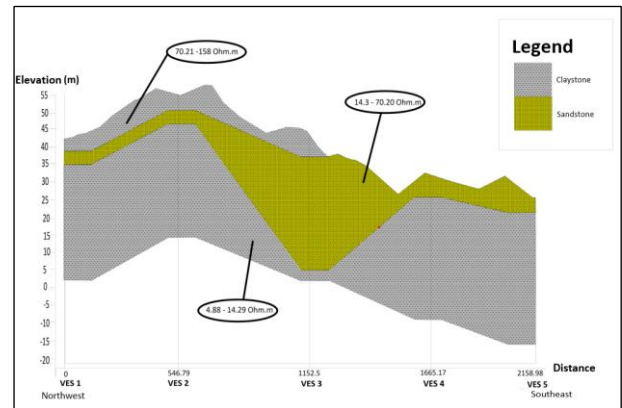


Fig 1. Correlation of 5 VES resistivity data points (Zein & Marshela, 2023)

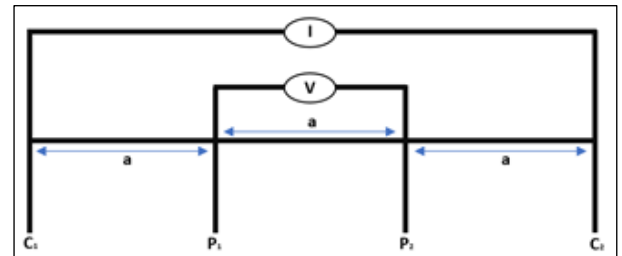


Fig 2. Wenner configuration array

Table 2. Grounding design input parameters

Parameter	Symbol	Value
Bus Fault	(kV)	115
Line to Line	I (kA)	1.98
Total Area	A (m ²)	2500
Duration of fault current	t_c (second)	0.5
	t_r (second)	
Constant	k_f	7.06
Ambient Temperature	T_a	40°C
Ratio of the system inductive reactance to resistance	\bar{X}	10
	\bar{R}	
Fault Duration	t_f (second)	0.5
Cycles	f (Hz)	60
Decrement Factor	D_f	1.026
Thermal Coefficient	α_r factor at 20°C (1/°C)	0.00378
	K_0 at 0°C (0°C)	
Maximum Allowable Temperature	T_m (°C)	1084
Resistivity of The Ground Conductor at Reference Temperature Tr	ρ_r ($\mu\Omega - cm$)	5.86
Thermal Capacity per Unit Volume	$TCAP$ ($\frac{J}{cm^3 \cdot ^\circ C}$)	3.8

VES technique generally uses 2 electrode pins (C1, C2) as electric current senders and 2 electrode pins (P1, P2) as signal receivers from electric current injected into the earth's surface. Wenner configuration is done by inserting current electrodes and potential electrodes in a straight line as in Fig. 2. The characteristic of the wenner configuration is the same distance between the electrodes (a). The greater the distance between the electrodes, the greater the

target depth sought, generally worth 1/3 of the total path length between electrode C1 to electrode C2.

$$R = 2\pi a \left(\frac{\Delta V}{I} \right) \quad (1)$$

Where $2\pi a$ is a geometric factor, ΔV is the potential difference in millivolts (mV), and I is the electric current in milliAmperes (mA).

2.2 Grounding

This study uses experimental data used as input for grounding design calculations can be seen in Table 2. In this study, it is assumed to use the gridding technique with or without rods. The main material used is copper (commercial hard drawn) with a conductivity level of 97%.

2.3 Grounding Design

The initial grounding design needs to consider and take into account several things. The grounding design uses 0.2 m thick crushed rock as a protective surface layer with a resistivity value of 2000 Ωm . The planned depth of the grid system to be planted in the ground is around 0.5 m. The planned installation area is square and rectangular by taking into account the same distance between grids. The use of rods in the grounding design uses the same length and number of rods. The number of grid conductors will differ depending on the shape of the installation area and the use of rods.

General grounding design analysis considers human safety factors. The weight value of a person is one of the references in determining the grounding design safety analysis factor. The average value taken is the average weight of an adult human of 50 kg and 70 kg. This aims to measure the maximum tolerance limit of the touch voltage E_{touch} and the potential E_{step} . The results of the tolerance value will be compared to the grounding design value made.

$$E_{touch50} = \frac{(1000+1.5 \times C_s \times \rho_s) 0.116}{\sqrt{t_s}} \quad (2)$$

$$E_{touch70} = \frac{(1000+1.5 \times C_s \times \rho_s) 0.157}{\sqrt{t_s}} \quad (3)$$

$$E_{step50} = \frac{(1000+6C_s \rho_s) 0.116}{\sqrt{t_s}} \quad (4)$$

$$E_{step70} = \frac{(1000+6C_s \rho_s) 0.157}{\sqrt{t_s}} \quad (5)$$

If there is no protective surface layer then the reduction factor C_s will be 1.

Ground Potential Rise (GPR) is the maximum voltage value of the system that must be sought to be compared

The third design parameter that must be sought is the step voltage value E_s . This parameter is shown by Eqn. 18 which represents the Step voltage between a point above the outer corner of the grid and a point 1 m diagonally outside the grid E_s . This value is influenced by several factors as shown by Eqn. 13, Eqn. 14, Eqn. 15, Eqn. 16, Eqn. 17) including Correction factor for grid geometry K_i , Geometric factor n , and Spacing factor for step voltage K_s (IEEE Power and Energy Society, 2013).

$$K_i = 0.148 \times n + 0.644 \quad (13)$$

$$K_s = \frac{1}{\pi} \left[\frac{1}{D} (1 - 0.5^{n-2}) + \frac{1}{h+D} + \frac{1}{h \times 2} \right] \quad (14)$$

$$n = n_d \times n_c \times n_b \times n_a \quad (15)$$

Eqn. 16, and Eqn.17 are used to obtain the total corrected geometry factor values n . Where $n_d = n_c$ has a value of 1 for square and rectangular shapes.

$$n_b = \sqrt{\frac{L_p}{\sqrt{A \times 4}}} \quad (16)$$

$$n_a = \frac{L_c \times 2}{L_p} \quad (17)$$

with the tolerance value of the touch voltage and potential. The GPR value can be obtained by multiplying the maximum current value of the grid system (I_G) by the grid resistance value of a system (R_g).

$$GPR = R_g \times I_G \quad (6)$$

Where the formula for finding the resistance value and maximum current of the grid system is shown in Eqn. 7 and Eqn. 8.

$$R_g = \rho \left[\left(1 + \frac{1}{1+h \sqrt{\frac{20}{A}}} \right) \left(\frac{1}{\sqrt{20A}} \right) + \frac{1}{L_T} \right] \quad (7)$$

$$I_G = 3I_0 \times S_f \times D_f \quad (8)$$

In the above context, the system resistance value is influenced by the depth of the system installation to be planted below the ground surface (h), the area of the system grid (A), the total length of the grid conductor required (L_T), and the soil resistivity value (ρ). The maximum system current value is influenced by Symmetrical fault current in substation for conductor sizing ($3I_0$) is, Fault current division factor (S_f), Decrement factor for determining and (D_f).

The second design parameter that must be sought is the mesh voltage value E_m . This value represents the maximum touch voltage as shown by Eqn. 12. This value is influenced by several factors as shown by Eqn. 9, Eqn. 10, Eqn. 11 including spacing factor for mesh voltage K_m , Corrective weighting factor for the effects of inner conductors on the corner mesh K_{ii} , and Corrective weighting factor that emphasizes the effects of grid depth K_h (IEEE Power and Energy Society, 2013).

$$K_m = \frac{1}{2 \times \pi} \left[\ln \left[\frac{8}{L(2 \times n - 1) \pi} \right] \times \frac{K_{ii}}{K_h} + \ln \left[\frac{((2 \times h) + D)^2}{8 \times d \times D} - \frac{h}{4 \times d} + \frac{D^2}{16 \times d \times h} \right] \right] \quad (9)$$

$$K_h = \sqrt{\frac{h}{h_0} + 1} \quad (10)$$

$$K_{ii} = \frac{1}{(n \times 2)^{\frac{2}{n}}} \quad (11)$$

The following is an equation for finding the mesh voltage value.

$$E_m = \frac{K_i \times I_G \times \rho \times K_m}{L_R \left[\left(\frac{L_r}{\sqrt{L_y^2 + L_z^2}} \right)^{1.22 + 1.55} + L_c \right]} \quad (12)$$

The following is an equation for finding the step voltage value.

$$E_s = \frac{K_i \times I_G \times \rho \times K_s}{L_R \times 0.85 + L_c \times 0.75} \quad (18)$$

3. Results and Discussion

The feasibility study of grounding design was carried out in the area where the resistivity test was carried out. In general, the area is divided into two groups, namely the first area is represented by the correlation of VES 1, VES 2, and VES 3 points with clay lithology, while the second area is represented by the correlation of VES 4 and VES 5 points with sand lithology. Grouping can be done by calculating the average value of soil resistivity in the lithology that is considered the same with the assumption of a depth of 0.5 m. The first area has a fairly high average resistivity value of 114.105 Ωm compared to the second area, which is 42.25 Ωm . Based on its corrosivity level, the clay area has a lower soil corrosive level (Neligible) than the sand area (Mildly Corrosive) (Zein and Marshela, 2023).

Table 3. The results of calculating the maximum tolerance value limits for touch and step potential.

Parameter	Weigh Body (kg)	Symbol	Value (V)
Tolerable touch voltage	50	$E_{touch50}$	572.5
Tolerable touch voltage	70	$E_{touch70}$	774.9
Tolerable step voltage	50	E_{step50}	1798
Tolerable step voltage	70	E_{step70}	2433.5

3.1. Square Shape with Rod VS Square Shape without Rod

The square area with grounding grid and rod design as shown in Fig. 4 has a total conductor length of 1228 m, while without rod as shown in Fig. 3 is 1000 m. The number of grids formed in the first and second square areas is 81. The number of rods to be installed in the square design is 48. The length of each rod planted underground is 6 m. The area of the grounding area square design is 2500 m² with a circumference of 200 m.

Table 4. Results of computing grounding design parameters in the Square area

Parameter	Symbol	Clay Area			Sand Area		
		With Rods	Without Rods	$\Delta_{withoutrods-withrods}$	With Rods	Without Rods	$\Delta_{withoutrods-withrods}$
Length in X direction	$L_x(m)$	50			50		
Length in Y direction	$L_y(m)$	50			50		
Total Grounding Area	$A(m^2)$	2500			2500		
Rod Number inline with X	n_x	10	-		10	-	
Rod Number inline with Y	n_y	10	-		10	-	
Geometric Factor	n	10			10		
Corrective factor	K_h		1.22			1.22	
	K_i		2.12			2.12	
	K_{ii}	1	0.55		1	0.55	
	K_m	0.72	0.84		0.72	0.84	
	K_s		0.43			0.43	
Grid Resistance	$R_g(\Omega)$	1.09	1.11		0.40	0.41	
Maximum Grid Current	$I_G(A)$	2033.50			2033.50		
Ground Potential Rise	$GPR(V)$	2211.10	2262.98	51.88	818.71	837.92	19.21
Mesh Voltage	$E_m(V)$	239.62	411.73	172.11	88.72	152.45	63.73
Step Voltage	$E_s(V)$	211.93	281.10	69.17	78.47	104.08	25.61

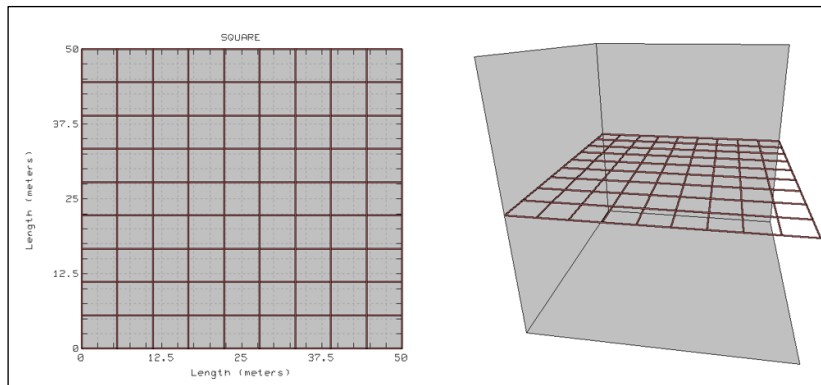


Fig 3. Grounding grid design without rod on square area

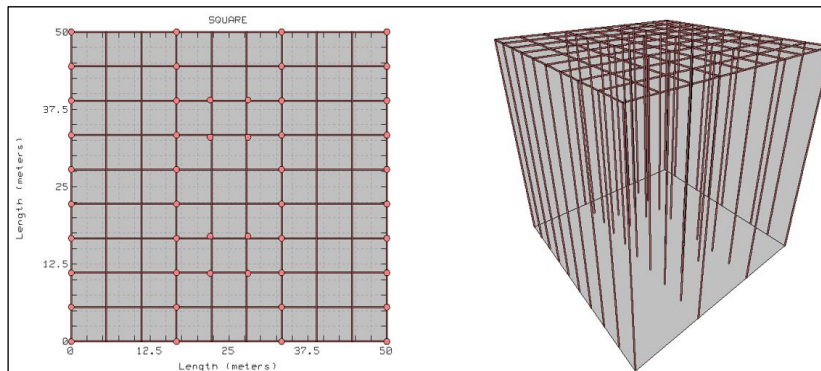


Fig 4. Grounding grid design with rod on square area

3.2. Rectangle Shape with Rod VS Rectangle Shape without Rod

The rectangle area with grid and rod design as shown in Fig. 6 has a conductor length of 288 m greater than without rod as shown in Fig 5, which is 1090 m. The

number of grids formed in the square area is 99. The number of rods to be installed in the square design is 48. The length of each rod planted underground is 6 m. The area of the two rectangle areas is 2475 m² with a circumference of 200 m.

Table 5. Results of computing grounding design parameters in the Rectangle area

Parameter	Symbol	Clay Area		$\Delta_{withoutrods-withrods}$	Sand Area		$\Delta_{withoutrods-withrods}$
		With Rods	Without Rods		With Rods	Without Rods	
Length in X direction	$L_x (m)$	45			45		
Length in Y direction	$L_y (m)$	55			55		
Total Grounding Area	$A (m^2)$	2475			2475		
Rod Number inline with X	n_x	12	-		12	-	
Rod Number inline with Y	n_y	10	-		10	-	
Geometric Factor	n	10.93			10.93		
Corrective factor	K_h		1.22			1.22	
	K_i		2.26			2.26	
	K_{ii}	1	0.57		1	0.57	
	K_m	0.68	0.79		0.68	0.79	
	K_s		0.44			0.44	
Grid Resistance	$R_g (\Omega)$	1.09	1.11		0.40	0.41	
Maximum Grid Current	$I_G (A)$	2033.50			2033.50		
Ground Potential Rise	$GPR (V)$	2209.35	2253.84	44.49	818.06	834.54	19.21
Mesh Voltage	$E_m (V)$	226.47	382.11	155.64	83.85	141.48	63.73
Step Voltage	$E_s (V)$	217.10	282.10	65	80.38	104.46	25.61

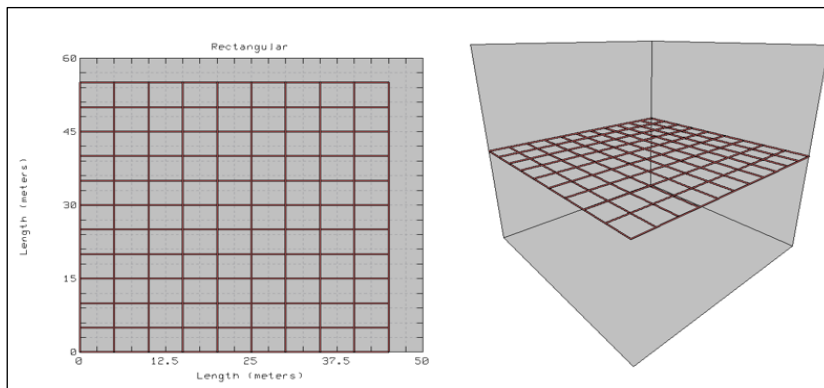


Fig 5. Grounding grid design without rod on rectangle area

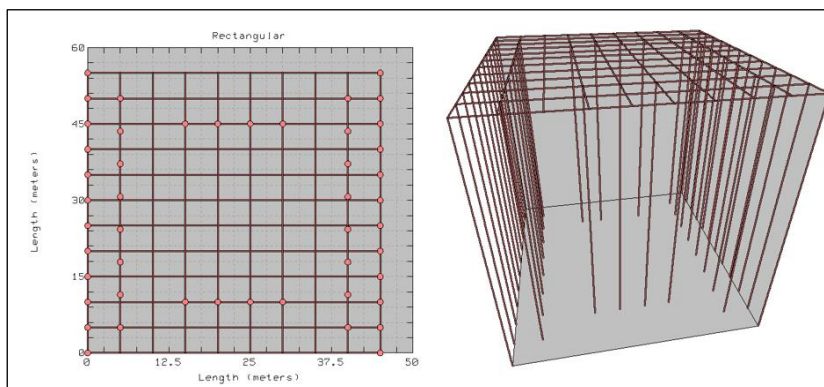


Fig 6. Grounding grid design with rod on rectangle area

3.3. Square Shape with Rod VS Rectangle Shape with Rod

It is known from the data in Table 4 and Table 5, the use of rods in the grounding design in clay and sand areas

makes the actual step and potential mesh values smaller than without using rods. The values that have been obtained can then be compared with the maximum tolerance value limits in the case of human weights of 50 kg and 70 kg as shown in Table 3 and Table 6. The expected actual design value must be smaller than the permitted tolerance value to be categorized as safe.

The Ground Potential Rise value in both the square and rectangle areas is compared with the potential touch and step tolerance values. The sand area produces a smaller actual design value compared to the clay area, which is around 818 V. This value is compared with the potential touch tolerance value of 572.5 – 774.49 V, resulting in a safe with note statement. This requires further analysis by comparing the potential Mesh design value to the potential touch tolerance value. When comparing the GPR value with the step tolerance value of 1798 – 2433.5 V, it produces an

applicable note in the sand area and safe with note in the clay area. Applicable means that the design made can be said to be safe, while safe with note means that further analysis is needed by comparing the potential step design value with the tolerance value.

Determination of mesh design value and potential step is a further verification to assess whether the grounding design made is safe or not. The smallest potential mesh value is produced in the sand area with a value of 83.85 V, while in the clay area it is 226.47 V. This value is lower than the maximum tolerance limit of touch potential 572.5 – 774.49 V so it can be categorized as safe. The smallest potential step design value is produced in the sand area with a value of 78.47 V, while in the clay area it is 211.93 V. This value is lower than the maximum tolerance limit of step potential 1798 – 2433.5 V so it can be categorized as safe.

Table 6. Comparison of potential values and tolerances of grounding design of square area with rod vs rectangular area with rod

Parameter	Shape	Area	Value	$\Delta_{clay-sand}$	E_{touch}				E_{step}			
					50 Kg	Remark	70 Kg	Remark	50 Kg	Remark	70 Kg	Remark
Ground Potential Rise GPR (V)	Square	Clay	2211.10	1392.39	Versus	572.5	Safe with Note	774.9	1798	Safe with Note	2433.5	Applicable
		Sand	818.71									
Mesh Voltage E_m (V)	Rectangle	Clay	2209.35	150.90		572.5	Safe	774.9	1798	Safe	2433.5	-
		Sand	818.06									
Step Voltage E_s (V)	Square	Clay	239.62	133.46		572.5	Safe	774.9	1798	Safe	2433.5	-
		Sand	88.72									
	Rectangle	Clay	226.47	136.72		572.5	Safe	774.9	1798	Safe	2433.5	-
		Sand	83.85									
	Square	Clay	211.93	136.72		572.5	Safe	774.9	1798	Safe	2433.5	-
		Sand	78.47									
	Rectangle	Clay	217.10	136.72	572.5	Safe	774.9	1798	Safe	2433.5	-	
		Sand	80.38									136.72

4. Conclusion

The resistivity value in an area is very important in assessing grounding design parameters such as calculating the Ground Potential Rise (GPR), step, and mesh potential values. The actual value of the planned grounding design parameters must be smaller than the permitted tolerance limit in order to be categorized as safe and feasible. The smaller the resistivity value in an area, the smaller the value of the grounding design parameters sought will be. However, the more rods and the total length of conductors installed in the grounding design, the smaller the actual value of the grounding design parameters will be.

In this study, the grounding design plan in sandy and clay areas with or without rod installations is categorized as feasible and safe. However, the difference in obtaining significant grounding design parameter values is influenced by the lithology resistivity of the area such as in sandy areas with an average value of 42.25 Ωm and clay areas which have an average value of 114.105 Ωm . In addition, the difference is influenced by the installation of 48 rods in the grounding system with no rods installed at all.

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