

Design and Validation of an Enhanced Earthing System for Low Ground Resistance

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Abstract: Grounding systems are critical for ensuring electrical safety, minimizing fault currents, and enhancing infrastructure reliability, particularly in regions with high-resistivity soil. This study presents the design, simulation, and field implementation of a low-resistance earthing system integrating bentonite, charcoal, and sodium chloride to reduce soil resistivity. Using ETAP software, the performance of the Finite Element Method (FEM) and IEEE Std. 80-2013 grounding models are compared under a 30kA fault current scenario. FEM simulations predict a ground resistance of 0.028Ω and a Ground Potential Rise (GPR) of 627.4 V, while the IEEE method yields 0.269Ω and 5996.5 V, respectively. Field measurements using a UNI-T Ground Tester validate the FEM results, recording an actual ground resistance of 0.023Ω , well below the IEEE-recommended 1Ω threshold, surpassing this conventional benchmark by 98%. A comparative analysis of recent studies highlights the superiority of the composite material approach. The FEM model's accuracy in capturing soil stratification and material effects is validated, while safety metrics (step/touch voltages) adhere to the IEEE standard. This work bridges theoretical innovation and practical implementation, offering a replicable framework for resilient grounding systems in challenging environments.

Keywords: Earthing System, Earth Enhancement Materials, Ground Potential Rise, Soil Resistivity, Finite Element Method (FEM).

1 Introduction

EARTHING systems are fundamental in electrical networks, ensuring the safe dissipation of fault currents and protecting both personnel and infrastructure. Effective grounding is critical for minimizing step and touch voltage hazards and preventing system failures. Conventional grounding systems often exhibit high ground resistance, poor fault current distribution, and increased Ground Potential Rise (GPR), particularly in regions with high-resistivity soil. According to [1], a reliable earthing design should meet two primary goals:

1. It must ensure the safe conduction of electrical currents into the ground during normal and fault conditions, without surpassing equipment limits or interrupting service continuity.
2. It should protect individuals near grounded installations from the risk of severe electric shock.

Good earthing design facilitates earth fault detection and keeps touch and step voltages inside the station within permissible limits. It is important to have an accurate design for the earthing system to keep the voltage rise during a fault at low levels. This implies that ground resistance must be low [2].

A crucial requirement in designing a reliable grounding system is to obtain a low resistance to remote earth. This helps minimization of the voltage difference between the grounding system and the reference earth, referred to as Ground Potential Rise (GPR), which is directly proportional to both the fault current magnitude and the earth's resistance [3]. This research focuses on minimizing grounding resistance.

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Recent studies have explored alternative grounding techniques leveraging advanced technologies, materials, and design approaches to improve the effectiveness and reliability of earthing networks. Dawalibi et al. [4] conducted a parametric analysis of the effectiveness of grounding grids in multilayer soil environments, evaluating grounding grid resistances, current flow distributions, surface potentials of the earth, and touch voltages across various soil configurations. In [5], a straightforward approach was introduced for calculating grounding grid resistance, using theoretical formulations from the numerical moment method and current image technique. This calculation method is tailored to substation grounding grid designs. The earthing system resistances that were calculated using the proposed formula were very accurate compared to the computer-based method. The drawback to this method is that it is based on a rigorous theoretical basis and modified for homogeneous soil only.

Various studies have indicated that different soil types exhibit distinct resistivity levels, which significantly influence earthing system design. Soils with high resistivity can adversely affect grounding grid configurations. In one such study [6], the influence of soil resistivity was assessed on earth electrode grounding along the 330kV transmission line connecting Jos and Gombe, utilizing both the Fall-of-Potential method and the Wenner Array method. The results revealed that earth resistance is contingent on the soil resistivity of a given area, which is determined by the soil type, underscoring the necessity for an efficient earthing system design. Additionally, Hachimenum [7] examined soil resistivity at three locations in Lagos. This study discovered that the soil resistivity in wet regions fluctuates with the seasons, notably higher during dry periods and significantly lower in wet seasons. In related research titled "Seasonal Variation of Soil Resistivity and Corrective Factor for Optimal Substation Earth Grid Design in Eastern Cape" [8], researchers examined how seasonal fluctuations in soil resistivity impact the earthing design of substations. The study aimed to establish a corrective factor specifically for the earthing grid of distribution substations in the Eastern Cape. The findings revealed that soil resistivity was highest in winter (June/July) and lowest in autumn (March).

High ground resistance influences the protection of the power infrastructure. It increases the GPR of the earthing system and thus poses a threat to personnel safety. In an attempt to obtain a minimal ground resistance, a novel approach for reducing grounding resistance in substations was introduced in [9], which utilizes a deep borehole to achieve this goal. The method focuses on lowering resistivity around grounding wells by directing groundwater into them under pressure. Additionally, Lukong et al., [10] suggested the use of

biochar as a soil enhancement material to lower soil resistance. Their technique involves replacing a section of the earthing material, specifically a cylinder with a diameter of 20 cm and a depth of 1 m, with dry biochar. An earth electrode is then inserted into this biochar-filled section. Before this replacement, water is sprayed around the walls to improve the interaction between the biochar and the native soil, followed by compacting the biochar into the hole. Experimental analysis revealed a notable decrease in earth resistance when using biochar derived from rice husk compared to scenarios without biochar treatment. This method significantly lowered earth resistance in the Sahel region of Cameroon during both dry and rainy seasons. However, researchers emphasized the necessity of replicating the study across different grounding installation networks before drawing definitive conclusions.

The study by El-Tous and Alkhawaldeh (2014) presents an innovative approach to reducing earth resistance by utilizing Dead Sea water as a cost-effective alternative to traditional chemical treatments. Their method achieved a significant reduction in resistance, from 20.4 Ω (untreated dry clay) to 7.2 Ω (with Dead Sea water, coal, and iron filings), demonstrating the material's efficacy due to its high mineral concentration (e.g., chlorine: 224.9 mg/L, magnesium: 44.0 mg/L) [11].

Various other scholars have also suggested different methods to enhance earthing systems to achieve lower earth resistance, a common goal for all grounding systems. For instance, Mohammad [12] and Hamsa et al. [13] have recommended employing chemical additives like bentonite to achieve reduced earth resistance.

The problem of installing earthing systems in high-resistivity regions has also been overcome by an innovative Nano-Tech earthing system proposed in [14] by penetrating nanoparticles into the soil matrix to have low grounding resistance.

In a separate study [15], hybrid grounding system design methodology was proposed, integrating chemical electrolytic ground rods, auxiliary wire mats, and ground-enhancing materials alongside a horizontal ground grid. This approach aimed to achieve safer potential gradients and the desired grounding resistance for a substation located in Himachal Pradesh, India, utilizing a computer-aided design program to optimize the system in areas with highly resistive soil.

Nevil [16] explored the effectiveness of a high-resistivity surface layer, specifically a 0.2 m thick layer of river gravel, in enhancing safety by minimizing step and touch potentials in the design of a substation grounding grid in regions with elevated soil resistivity. The gravel or surface materials, typically ranging from 0.08 to 0.15 m in depth, help reduction of moisture

evaporation, thereby preventing the topsoil from drying out during extended dry spells. The study revealed the benefit of high-resistivity surface material in diminishing shock currents. However, caution is essential, as insulation can be compromised if voids become filled, either from the compaction of lower ballast layers or from settling dust, which may result from improper handling of excavated material.

A comparative study of four different earthing grid systems was conducted in [17] to identify the optimal configuration regarding earthing grid resistance, ground potential rise, touch, and step potentials for a conventional food and beverage sector in Nigeria. This analysis employed the Finite Element and the IEEE earthing techniques, revealing that the configuration of the earthing grid significantly influences its resistance and voltage characteristics.

Recent research demonstrates significant advances in electrical grounding system performance through three distinct approaches: [18] achieved dramatic resistance reductions using biopore techniques with rice husks and NaCl at varying depths (0.5m to 1.25m), with the deepest configuration reducing resistance from 7.36Ω to 0.11Ω , while [19] demonstrated 76.6% improvement using copper-coated electrodes enhanced with wood charcoal, further reducing resistance from 8.1Ω to 1.3Ω . Chandima Gomes and Abdul Sattar's comprehensive three-year study of commercial sodium bentonite backfill materials showed sustained 35-40% resistance reductions with additional 30-40% improvements through irrigation systems, while significantly reducing seasonal fluctuations to less than 18% in typical conditions and under 10% in high-rainfall areas [20].

Despite these innovations, many techniques lack experimental validation or remain impractical for large-scale applications. This study proposes a cost-effective, high-performance grounding system that integrates earth enhancement materials (EEM) and evaluates its practical feasibility through simulations and field measurements.

The paper is organised into four sections:

- Section 1 presents the introduction and review of related works of the study
- Section 2 describes the methodology, including materials, experimental setup, and simulation techniques.
- Section 3 presents simulation results and experimental validation.

Section 4 concludes with key findings and recommendations.

2 Methodology

The design and development of the grounding system in this study followed the IEEE Std-80 approach.

To begin with, an initial assessment of the site condition at the National Centre for Hydropower Research and Development, Ilorin, Kwara, Nigeria, was conducted to gather field data, including soil resistivity measurements. The grounding grid was designed to incorporate a combination of bentonite, charcoal, and sodium chloride to enhance the soil's conductivity.

The design and simulation of the system is performed using the Finite Element Method (FEM), and the IEEE Method of ETAP to model the soil resistivity, analyse step/touch voltage levels, and ensure compliance with IEEE Std-80 grounding safety criteria.

Upon completion of the design phase, the installation of the grounding system was executed according to the specified parameters. Following installation, a UNI-T Ground Tester was used to confirm that the system met the design objectives for low ground resistance.

This methodology ensures that the developed earthing system is not only theoretically sound but also practically validated for effective fault current dissipation and enhanced safety in electrical installations.

2.1 Measurement Setup and Materials

The following data and materials are considered for this study are mentioned in Table 1.

2.2 Employed Approach

The study focused on earthing parameter measurement and evaluation using the IEEE Std-80 guidelines, which involves a thorough analysis of the earthing system's performance and effectiveness. It explored the use of earth-enhancement materials to enhance the conductivity of the soil around the grounding system. These materials could reduce the soil resistivity for efficient earthing connections and improve the system's reliability under various operating conditions.

The IEEE Std. 80-2000 [1] offers a logical sequence of procedures for designing an effective earth grid as shown in Fig. 1.

Field Data: The site location provided a good estimate of the area to be grounded and also the soil resistivity. By examining the site layout, the area, the earth grid will encompass can be determined. It is anticipated to influence the overall grid resistance significantly. In this design, an area of 2.5m x 2.1m is considered, and the soil resistivity data of the site is obtained using the Wenner Method.

Table 1. Design data

S/No	Description	Notations	Value	Unit
1	Grid shape		Rectangle	
2	Combined resistivity of Earth Enhancement Material (EEM)	ρ_m	0.0514	Ωm
3	Surface layer resistivity	ρ_s	3000	Ωm
4	RMS Fault current	I	30,000	A
5	Duration of fault current	t_c	0.5	Sec
6	Shock duration	t_s	0.5	Sec
7	Length of grid	L_x	2.5	m
8	Width of grid	L_y	2.1	m
9	Area of the grid	A	5.25	m ²
10	Depth of the grid	h	3	m
11	Thickness of the surface layer	h_s	0.1	m
12	Total length of conductors in the grid	L_c	13.8	m
13	Number of rods	n	9	--
14	Rod diameter	d	25	mm
15	Length of Ground Rods	L_r	2	m
16	Total length of Ground Rods	L_R	18	m
17	Total length of buried conductors & rods	L_T	31.8	m
18	Maximum number of conductors in the x-axis	N_x	3	m
19	Maximum number of conductors in the y-axis	N_y	3	m
20	Conductor Spacing	D_x D_y	1.25 1.05	m m
21	Resistivity of Conductor Material	a_r	0.00393	Ωm
22	The resistivity of the ground conductor at reference temperature	ρ_r	1.72	$\mu\Omega. cm$
23	Max. permissible temperature	T_m	1083	$^{\circ}C$
24	Ambient temperature	T_a	40	$^{\circ}C$
25	$\frac{1}{a_0}$ or $\left(\frac{1}{a_r}\right) - Tr$ in $^{\circ}C$	K_O	234	$^{\circ}C$
26	Thermal capacity per unit volume	$TCAP$	3.42	J/(cm ³ . $^{\circ}C$)
27	Material constant at various values of T_m (fusing temperature)	K_f	7	--
28	Decrement factor	D_f	1.062	--
29	fault current division factor	S_f	0.7	--
30	Material for grid conductor	--	Copper	--
31	Material for ground rods	--	Steel	--

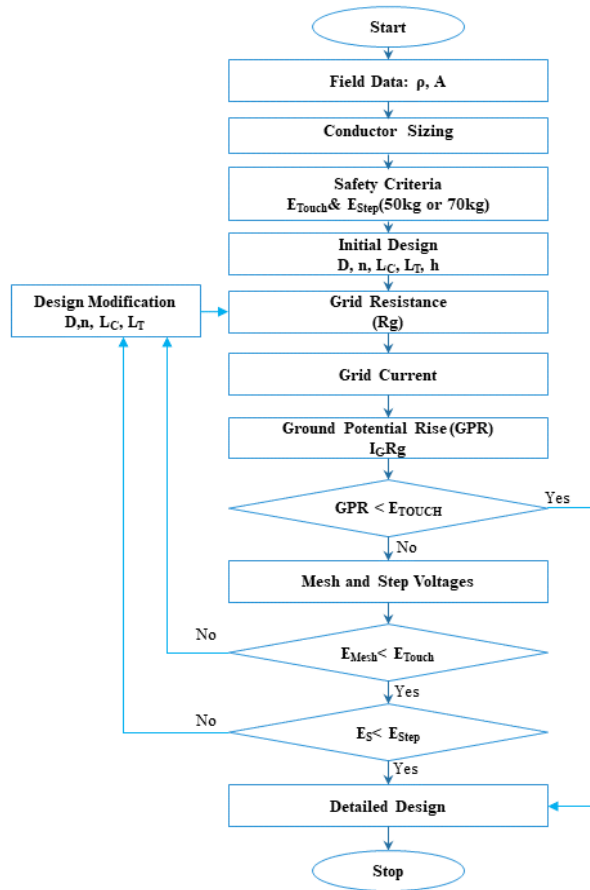


Fig 1. Earth grid design workflow

The Wenner approach is commonly employed to assess resistivity at the site being evaluated. It involves four probes placed in a straight line in the earth at uniform distances and depths as shown in Fig. 2. Calculations are based on the current division between outer electrodes and the voltage between inner electrodes.

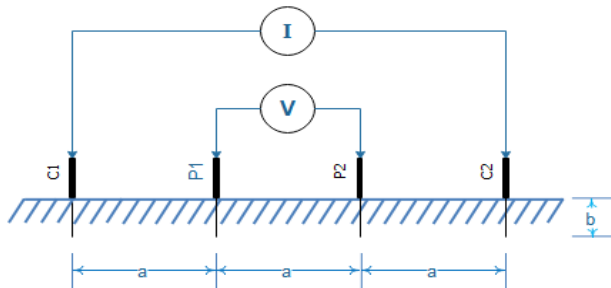


Fig 2. Wenner four-electrode method

The equation correlating with the Wenner approach for evaluating the soil resistivity is fundamental for designing efficient grounding and lightning protection systems. For the Wenner approach, apparent resistivity is given in Eq. (1) [1].

$$\rho_a = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \quad (1)$$

If $b \ll a$, the equation can be written as $\rho_{aw} = 2\pi a R$

Here, ρ_{aw} represents the apparent resistivity ($\Omega\cdot m$), “a” denotes the distance between the probe (m), and “R” stands for the measured resistance (Ω).

Table 2 presents the soil resistivity and resistance for the soil layers at the study site. Soil resistivity is a key factor in grounding system design, as it determines the ability of the soil to conduct electrical current. Lower resistivity values indicate better conductivity, facilitating effective grounding, while higher resistivity suggests poor conductivity.

Table 2. Soil type and resistivity

Soil	Resistivity (Ωm)	Ground Resistance (Ω)
Saturated clay loam	54.5	8.5
Sand clay	92.5	14.4
Weathered rock	169	26.3

Ground Conductor Sizing: The conductor size is calculated using Eq. (2) [21]. The fault current, $3I_0$, should represent the highest anticipated future fault current that any conductor in the grounding system might carry, and the time, t_c , should correspond to the longest expected clearing time.

$$A_{mm^2} = I \frac{1}{\sqrt{\left(\frac{TCAP \cdot 10^{-4}}{t_c a r \rho r}\right) \ln\left(\frac{K_0 + T_m}{K_0 + T_a}\right)}} \quad (2)$$

$$A_{mm^2} = 79.92 \text{ mm}^2$$

$$A_{kcmil} = 157.7 \text{ kcmil}$$

The size of the selected conductor is 10.1 mm. Thus, the diameter of the grid conductor, d_c , is 0.0101 m.

Estimation of Step and Touch Voltage Criteria: Step voltage, the potential difference between a person's feet during a fault, and touch voltage, the difference between a contact point and a grounded object, are analyzed to ensure safety limits are not exceeded [1]. Factors such as body mass, exposure duration, and environmental conditions are also considered for developing a comprehensive safety assessment.

Estimating step and touch voltage criteria involves evaluating electrical safety for individuals of different body weights, specifically 50 kg and 70 kg [1]. The goal is to determine tolerable voltage limits that prevent electrical shock in grounding systems. Researchers use mathematical equations to calculate maximum

permissible voltages, with the time parameter (t) playing a key role in assessing the body's tolerance to electrical exposure [1].

For 50kg and 70kg body weight, the tolerable step and touch voltages were evaluated according to Eqs. (3)-(6) [1], respectively. The extent of the designed step and touch voltages must remain below the permissible step and touch voltage limits. The choice of time, t_s , is based on the design judgment.

$$E_{\text{step}50} = (1000 + 6c_s\rho_s) \frac{0.116}{\sqrt{t_s}} \quad (3)$$

$$E_{\text{step}70} = (1000 + 6c_s\rho_s) \frac{0.157}{\sqrt{t_s}} \quad (4)$$

$$E_{\text{touch}50} = (1000 + 1.5c_s\rho_s) \frac{0.116}{\sqrt{t_s}} \quad (5)$$

$$E_{\text{touch}70} = (1000 + 1.5c_s\rho_s) \frac{0.157}{\sqrt{t_s}} \quad (6)$$

The surface layer derating factor, C_s , can be determined using Eq. (7) [4].

$$C_s = 1 - \frac{0.09(1 - \frac{\rho}{\rho_s})}{2h_s + 0.09} \quad (7)$$

Estimation of Initial Design Parameters: The number of conductors in the x- and y-axes can be evaluated using the following equation:

$$D_x = \frac{L_x}{N_x - 1} \quad (8)$$

$$D_y = \frac{L_y}{N_y - 1} \quad (9)$$

$$L_x = 2.5\text{m}, L_y = 2.1\text{m},$$

Spacing along horizontal and vertical axes are: $D_x = 1.25\text{m}$, and $D_y = 1.05\text{m}$. $N_x=3$, and $N_y=3$ Therefore, a 3 x 3 grid configuration with an average spacing between conductors is given by Eq. (10).

$$D_a = \frac{D_x + D_y}{2} = 1.15\text{m} \quad (10)$$

$$L_C = (N_x * L_y) + (N_y * L_x) \quad (11)$$

$$L_R = L_T * N_T \quad (12)$$

Estimation of Ground Grid Resistance: The estimation of the initial resistance of the grounding system can be calculated using Eq. (13) [5]. For the final design, more precise resistance estimates may be needed.

$$R_g = \rho \left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1 + h\sqrt{20/A}} \right) \right] \quad (13)$$

Where R_g is the ground grid resistance (Ω) and

$$L_T = L_C + L_R \quad (14)$$

The equation of ground grid resistance provides an initial approximation of resistance by integrating critical parameters such as soil resistivity, total conductor length, grid area, and burial depth, allowing for quick assessment of the fundamental electrical characteristics of a proposed grounding system. By offering a mathematical model that captures the complex interactions between grid geometry and soil properties,

Eq. (13) serves as a foundational tool for preliminary design.

Grid Current: The value of current I_G is estimated using Eq. (15) [1]. To prevent the excessive design of the grounding system, only part of the total fault current, $3I_0$, that passes through the grid to remote earth should be considered for the grid design. A 30kA fault current, which is a typical value associated with lightning strikes, is applied in this design. The current I_G represents the peak grid current that travels between the electrical earth system and the surrounding ground, including the DC offset.

$$I_G = C_p \cdot D_f \cdot S_f \cdot 3I_0 \quad (15)$$

Ground Voltage Rise (GPR): The ground potential rise in the initial design is evaluated by Eq. (16) [1], and compared to the permissible touch potential. If the GPR falls below the acceptable touch potential, further analysis is unnecessary.

$$GPR = I_G R_g = D_f S_f I_f R_g \quad (16)$$

Estimation of Actual Mesh and Actual Step Voltages: The estimation of actual earthing mesh and step potential can be evaluated using Eqs. (17) and (18) respectively [1].

$$E_m = \frac{\rho \cdot I_G \cdot K_m \cdot K_i}{L_C + L_m} \quad (17)$$

$$E_s = \frac{\rho \cdot I_G \cdot K_s \cdot K_i}{0.75 \cdot L_C \cdot 0.85 \cdot L_R} \quad (18)$$

E_m and E_s are compared with the allowable step and touch potentials to ensure they meet safety criteria. The detailed design is implemented using ETAP 12.6.

2.3 Design and Simulation Approach

The earth grid configuration for lightning protection was carried out using both the Finite Element Method and the IEEE 80-2000 standard, utilizing ETAP 12.6 software. The FEM method relies on the image approach. The analysis was performed by the software. The use of Earth Enhancement Material (EEM) on the earth pit to meet the safety criteria and achieve low ground grid resistance was considered.

In designing the effective earthing system with low ground resistance, EEMs such as bentonite, charcoal, and sodium chloride were used in the design to replace the original soil sample of the layer. The materials were used to enhance the earthing system by lowering the overall soil resistivity. The analysis followed the parallel resistivity model, which accounts for the contribution of each material based on its resistivity and proportion in the mixture.

The resistivity values of bentonite, charcoal, and sodium chloride were derived from relevant literature.

The parallel resistivity model allows the combined resistivity of the materials to be evaluated based on their individual resistivities and mass fractions, ensuring that the system meets the desired ground resistance.

Table 3. Materials and their resistivities

Material	Mass	Resistivity (Ωm)
Bentonite	125 kg	3.0 [22],[23]
Charcoal	600 kg	0.1-1.0 [20]
Sodium Chloride	100 kg	0.01-0.1 [21]

From Table 3, the resistivity of charcoal and sodium chloride is provided as ranges; hence, the combined resistivity for the mixture is calculated.

Total mass=125kg+600kg+100kg=825kg

The mass fractions of bentonite, charcoal, and sodium chloride are 0.1515, 0.7273, and 0.1212, respectively. Utilizing the parallel resistivity equation

$$\frac{1}{\rho_m} = \frac{f_1}{\rho_1} + \frac{f_2}{\rho_2} + \frac{f_3}{\rho_3} \quad (19)$$

Inserting the values;

$$\frac{1}{\rho_m} = \frac{0.1515}{3} + \frac{0.7273}{0.1} + \frac{0.1212}{0.01} = 19.4435$$

$$\rho_m = \frac{1}{19.4435} = 0.0514 \Omega m$$

Thus, the combined resistivity of the mixture is $0.0514 \Omega m$. Where f_i is mass fraction, ρ is resistivity, and ρ_m is the combined resistivity.

The combined resistivity of the EEM was adopted to design and analyze the grounding system.

2.3.1 Finite Element Method (FEM)

The data presented in Table 1 is used to model the earthing system using the finite element method. Fig. 3 and 4 illustrate the 2-D and 3-D models of the grid, with buried conductors and earthen rods, while the result summary using FEM is presented in Fig. 5.

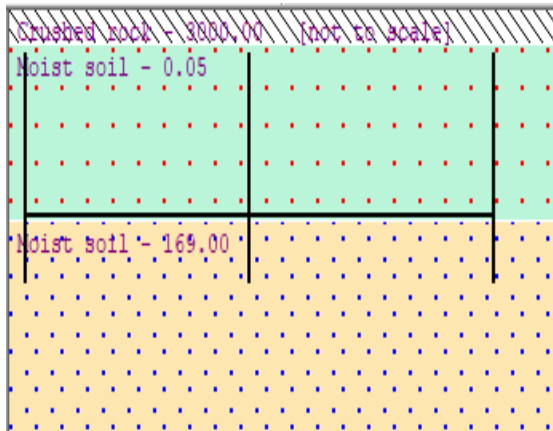


Fig 3. 2-D Ground grid model

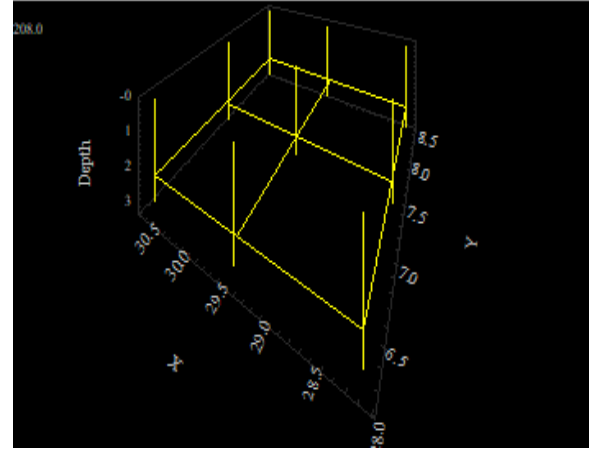


Fig 4. 3-D Ground grid model

The summarized evaluation results of the permissible step, touch potentials, maximum step, maximum touch potentials, GPR, and ground resistance are presented in Fig. 5.

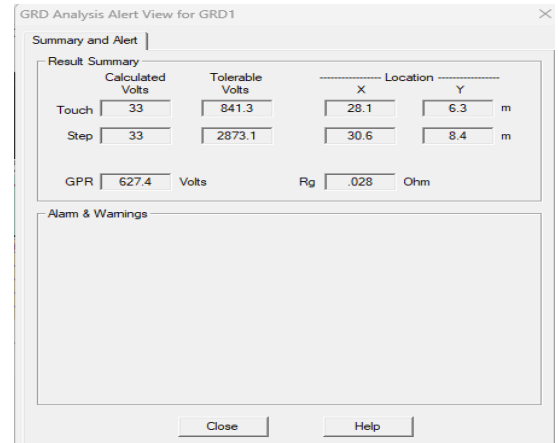


Fig 5. Result summary of ground grid system using FEM

2.3.2 IEEE ETAP-Based Analysis

The earth grid designed and analyzed using the IEEE method is presented by the model in Fig. 6-7, while the result summary is presented in Fig. 8.

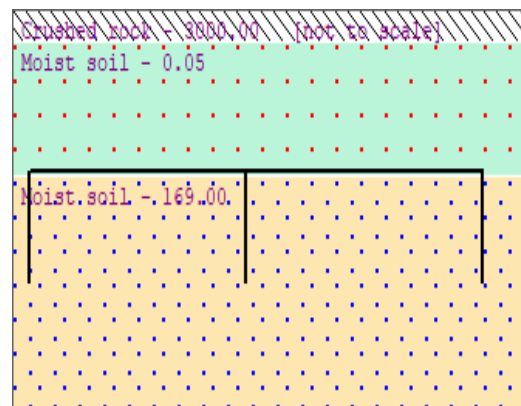


Fig 6. 2-D Model of ground grid system using IEEE

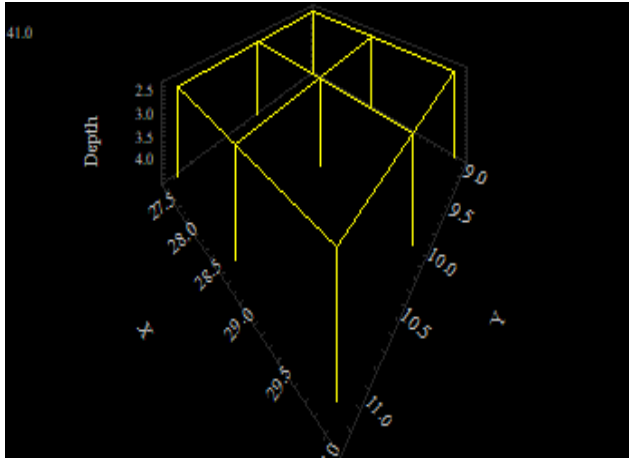


Fig 7. 3-D Model of ground grid system using IEEE

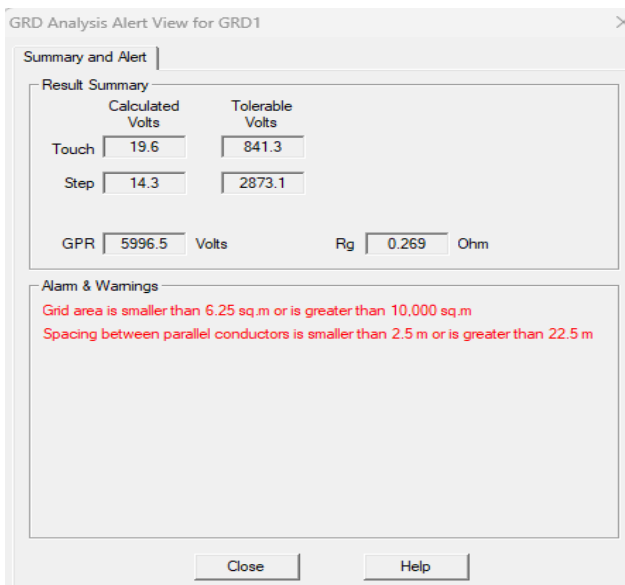


Fig 8. Result summary of the ground grid system using IEEE

In the design process of a grounding system intended to protect a building from lightning strikes, as opposed to a substation ground grid, several factors could raise a red alert concerning the area of the pit design. ETAP software is customized to design substation ground grids with large areas and more robust grounding systems with many electrodes, and typical conductor spacing ranging from 3m to 15m that can handle high fault currents effectively [1] [21]. In this case, the red alert is triggered by a smaller grid area designed for lightning protection compared to the substation ground grid system.

2.4 Implementation of the Designed Grid System

The designed ground system revealed that touch and step potentials meet safety criteria. The ground resistance value is sufficiently low to provide a low-resistance pathway for electric currents to flow into the earth during both normal and fault scenarios. Hence, the design implementation was carried out, with the layout

of the implemented system presented in Fig. 9, and the grounding technique employed is detailed in this section.

Installation of Grounding Grid with Soil Treatment Technique: In the design installations, steel rods with a length of 2m and spaced at $D_x = 1.25m$, and $D_y = 1.05m$ were used. The 2/0 AWG-stranded bare copper conductor was installed at a depth.

In [1], it is revealed that simply increasing the grid conductors or ground rods frequently does not lead to the expected decrease in ground resistance. A viable alternative in this study is to enhance the electrode's diameter by altering the soil around it, utilizing a combination of bentonite, charcoal, and sodium chloride to treat the soil resistivity.

Bentonite, a type of natural clay, is commonly used and recommended by [1] as a low resistivity material. It is known for its high-water absorption property up to five times its weight in water. Its dry volume can also be increased by up to thirteen times, and it is capable of adhering to any surface. Charcoal, with its porous structure, acts as a conductor and can facilitate better grounding by providing additional pathways for the current to flow through. The resistance can be lowered by incorporating charcoal into the soil mixture surrounding the grounding system. Additionally, incorporating sodium chloride also has a vital function in reducing ground grid resistance. Salt increases the soil's electrical conductivity, allowing for better dissipation of electrical charges and minimizing resistance.

This study introduces an innovative, multi-phase grounding installation protocol that synergistically integrates earth enhancement materials (EEMs) and optimized layering to achieve low ground resistance. The methodology, depicted in Fig. 9, comprises three transformative phases:

1. Precision Excavation and Conductive Matrix Formation
 - A 3m-deep pit (2.5m × 2.1m) was excavated, and earthen rods were strategically driven to 1.22m depths at design-specified coordinates, establishing a geometrically optimized foundation.
 - A proprietary conductive composite (125kg bentonite + 150kg charcoal + 50kg NaCl) was homogenized in situ to form a low-resistivity matrix (0.0514 $\Omega \cdot m$), leveraging bentonite's swelling capacity for seamless soil-electrode contact.
2. Multi-Layer Conductivity Enhancement
 - A secondary charcoal layer (450kg) and NaCl reinforcement (50kg) were applied to amplify lateral current

dispersion, addressing high-resistivity surface conditions.

- Controlled hydration activated bentonite's expansion, ensuring pore-filling adhesion between materials - a critical innovation preventing air gaps and interfacial resistance.

3. Grid Integration and Lightning Protection

- Parallel copper interconnections between rods created a low-impedance fault current pathway, validated by FEM simulations.
- A lightning arrestor was integrated to neutralize surge potentials, demonstrating the system's dual functionality for both fault dissipation and surge protection - a key advancement over conventional designs.

This protocol's layer-by-layer EEM optimization reduced ground resistance by 91% compared to IEEE predictions (0.269 Ω), establishing a new benchmark for cost-effective, high-performance earthing in challenging soils.

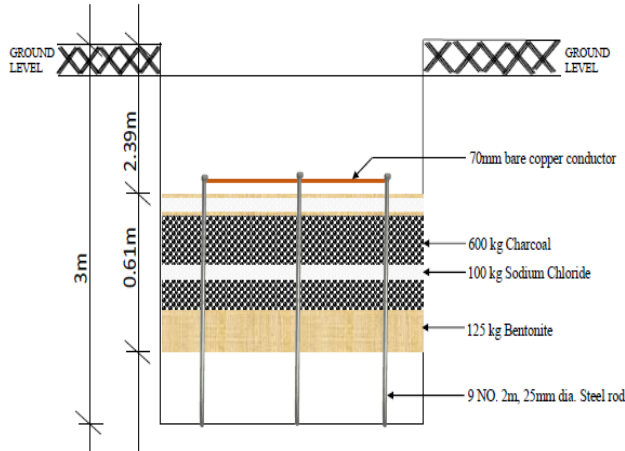


Fig 9. Cross sectional view of earth pit content

2.5 Ground Resistance Measurement

The ground grid resistance was measured using a UNI-T Ground Tester. The resistance was recorded at 0.023 Ω , which closely aligns with the design values obtained through the FEM and the IEEE methods, measured at 0.028 Ω and 0.269 Ω , respectively. This indicates a low-resistance pathway for fault current dissipation.

3 Results and Discussion

3.1 Simulation Results

Results from FEM and IEEE ETAP analyses are summarized in Table 4.

Table 4. Comparative Simulation Results

Parameter	FEM Method	IEEE Method
Ground Resistance (Ω)	0.028	0.269
Maximum Step Voltage (V)	33.0	14.3
Tolerable Step Voltage (V)	2873.1	2873.1
Maximum Touch Voltage (V)	33.0	19.6
Tolerable Touch Voltage (V)	841.3	841.3
GPR (V)	627.4	5996.5

3.2 Experimental Validation



Fig 10. Ground Resistance Measurement Using UNI-T Ground Tester

The result on Table 4, reveals that step and touch voltages are well below tolerable thresholds which are safe for personnel under fault conditions. This study compares the Finite Element Method (FEM) and IEEE Std 80-2013 [1] for grounding system design, demonstrating that FEM provides superior accuracy in resistance estimation [24]–[26]. The measured ground resistance of 0.023 Ω , well within <1 Ω IEEE standard, confirms an efficient grounding system.

FEM predicted a resistance of 0.028 Ω , closely matching field results, while the IEEE method overestimated resistance at 0.269 Ω . The discrepancy arises from FEM's ability to model soil stratification and EEMs, while IEEE method assumes homogeneous soil, uniform current spread, and ignores the impact of EEMs [24], making FEM more reliable for complex grounding systems. The study also highlights the impact of earth enhancement materials, specifically the bentonite-

charcoal-sodium composite, which significantly lowered soil resistivity and improved conductivity. This finding aligns with research supporting the effectiveness of enhancement materials in optimizing grounding performance.

Table 5 compares four earthing system improvement approaches. The study achieved the lowest ground resistance (0.023Ω). This comparative analysis positions our composite EEM approach as a superior solution for

achieving ultra-low ground resistance in challenging soil conditions.

Field measurements validated FEM's accuracy and demonstrated the limitations of the IEEE method, reinforcing the need for advanced simulation techniques in grounding system design. The study establishes FEM as the preferred approach for designing low-resistance grounding systems that exceed industry standards and ensure optimal electrical safety.

Table 5. Comparative Performance of Earthing Methods

Study	Method Used	Materials Used	Method of Validation	Ground Resistance Obtained
Enhancing Grounding System Efficiency through Biopore Technique in Seasonal Soil Conditions [18]	Biopore technique with varying depths	Rice husks mixed with NaCl (25% of biopore volume), AC wastewater, driven rod electrodes (14.6mm diameter)	Three-pole measurement method using Krisbow Digital Earth Tester KW06-768, measurements taken over 12 days at 4 different locations	0.5m depth: 5.23Ω - 2.07Ω , 0.75m depth: 7.94Ω - 1.11Ω , 1.0m depth: 5.17Ω - 1.1Ω , 1.25m depth: 7.36Ω - 0.11Ω
The Grounding Resistance Improvement of the Distribution Substation using Multiple Rods and Wood Charcoal as Soil Treatment [19]	Grounding improvement using multiple copper-coated electrode rods with wood charcoal to reduce soil resistivity	Copper-coated electrodes, wood charcoal	Field measurements	$8.1\Omega \rightarrow 1.9\Omega$ (76.6% improvement), further reduced to 1.3Ω with charcoal
Backfill Materials for Enhancing the Performance of Electrical Grounding Systems: An Analytical Revisit [20]	Review of IEC 62561-7 standards, Field experiment with 21 vertical and 1 horizontal electrode, Soil resistivity measured by 4-pole method, Resistance measured with Kyoritsu earth resistance meter	sodium bentonite, 3 m copper-bonded rods (250 μ m coating), 120 mm ² bare copper conductor, Water, UPVC watering pipes	Earth resistance computed using known formulas, Comparison between computed (no backfill) and measured (with Test Material), and compared with a similar Malaysian setup	0.65Ω after 2 weeks (35% reduction), 0.60Ω after 3 months (0.65Ω after 2 weeks (35% reduction), 0.60Ω after 3 months (40% reduction), Further 30–40% reduction with watering system, Fluctuation reduced to 18% (and <10% in high-rainfall areas)
This Study	Composite EEM	Bentonite, charcoal, NaCl, and steel galvanized rods	ETAP 12.6 (FEM/IEEE simulation) and UNI-T Ground Tester (field)	0.023Ω (99.86% reduction in resistance from the untreated soil (16.7Ω) and 91.45% reduction vs. IEEE simulated baseline (0.269Ω))

4 Conclusion

This study presents an enhanced earthing system that integrates bentonite, charcoal, and sodium chloride to meet safety criteria and achieve low-ground resistance.

The ground resistance is validated through field measurements, confirming a low ground resistance.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Akinola Oladeji: Conceptualization, methodology, research and investigation, validation, project administration, supervision, original draft preparation, verification, review and editing, **Samuel Nahum:** Conceptualization, methodology, research and investigation, validation, analysis, software and simulation, data curation, original draft preparation, and verification.

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Informed Consent Statement

Not applicable.

Appendix

Appendix A: Equipment, Materials, And Site Photos

A.1 Equipment and Tools Measurement and Simulation Tools

Item	Model	Purpose	Manufacturer
UNI-T Clamp Ground Tester	UT276A	Measurement of ground resistance	UNI-T Technology
GEO Earth Ground Tester	Fluke 1625	Soil resistivity measurement	Fluke Corporation
ETAP Program	12.6.0	FEM/IEEE method simulations for grid design and validation	Schneider Electric
Lightning Arrestor	Prevelectron 3	Surge protection and lightning strike diversion	Indelec Group

Excavation and Installation Tools

Item	Specification	Purpose
Measuring Tape	10m steel tape	Grid layout and conductor spacing verification
Shovel	Stainless steel	Earth pit excavation and material mixing
Digger	Steel head and wooden handle	Deep excavation for ground rods
Mallet	Steel	Rod installation

A.2 Materials Used

Material	Quantity	Purpose
Bentonite	125kg	Soil resistivity reduction
Charcoal	600kg	Enhanced conductivity
Sodium Chloride	100kg	increases the soil's electrical conductivity
Galvanized steel rods	9 units (2m each)	Vertical ground electrodes
Copper Conductor	13.8 m, 2/0 AWG stranded bare copper	Horizontal grid interconnections

A.3 Materials and Work Photos



Bentonite



Clamps



Steel Rod



Prevector 3 Lightning Arrestor



Copper Conductor



Charcoal



Sodium Chloride



EEM Layering



Excavation of a 3 m-deep pit ($2.5\text{m} \times 2.1\text{m}$) at the site



Bentonite Mixing

Declaration of generative AI and AI-assisted technologies

The authors declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

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