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ASSESSMENT OF THE EFFECT OF SOME FACTORS AFFECTING SOIL RESISTIVITY FOR OPTIMAL PERFORMANCE OF A GROUNDING SYSTEM

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ABSTRACT: The impedance of the discharge path of a fault current defines the quality of a grounding system. This study assessed the effect of depth (D), temperature (T), moisture content (MC) and soil texture (ST) on soil resistivity (ρ_s) for optimal performance of a grounding system. The ρ_s measurements for two seasons (rainy season-July 2023) and dry season-January 2024) were carried out at five different locations in Federal University of Agriculture, Abeokuta (FUNAAB), Nigeria as a case study. The ρ_s at the selected locations was measured via Wenner method using Herojat Rhomega-smart resistivity meter. The MC and ST were determined via laboratory analyses of five samples of soil, each of 5 kg, taken from each location at different values of D generated by the meter. The values of T at different D values were measured using a thermometer. The relationships between ρ_s and MC, T and D were modelled via multiple linear regression (MLR) for each location. The contributions of D, T and MC to ρ_s were determined by the coefficient of determination (R^2). The ρ_s obtained during the rainy and dry seasons over the study period at the test locations were observed to be influenced by D, ST, T and MC. The MLR models developed for the five locations for both seasons revealed that MC, T and D collectively contributed better to ρ_s than the individual variables due to higher value of multiple R^2 recorded. This study's findings could serve as useful guides for grounding system installation for FUNAAB and other areas with similar geophysical structures.

Keywords: Coefficient of determination, Fault current, Grounding system, Multiple linear regression, Soil resistivity

1. Introduction

Electricity, when available, is very useful in the running of the daily activities of human life. It is, however, a very dangerous quantity that can wreck huge havoc when mishandled. Adequate and appropriate grounding is required to halt undesirable flow of electricity, especially fault events [1-3]. Electricity generation, transmission, and distribution are capital-intensive processes requiring many sophisticated and interconnected components to come into fruition. These components need to be properly and sufficiently protected from damages and malfunctions arising from electrical energy leakages due to faults or other ill adventures. This requirement, therefore, paves way for a quality grounding system in power system that can safely discharge the electrical energy leakages without harm to the equipment, human or animal lives.
Equipment failures and significant human harm are both increased by a grounding system with high ground resistance because it creates a dangerous channel for the fault current [4-6]. If a fault

current in this situation cannot find a way to flow via a properly installed grounding system, it finds an alternative route, possibly through some high-tech apparatus or through a human body in some circumstances [7-9]. Harmonic distortion and instrumentation errors may occur as a result of poor grounding systems in any electrical and electronics systems. As a result, the need for a good grounding system that can offer the required low resistance for short circuit current under fault or ill events becomes imperative. It has been reported elsewhere that the need for a high quality grounding systems for efficient operation of electrical systems cannot be over-emphasized [10-12]. The variations in soil texture, temperature, moisture content, depth, and electrode size make it necessary for a grounding system's resistance to be carefully considered in order to ensure that fault current is efficiently transmitted to ground [13-15].

Fires emanating from electrical faults have caused numerous electrical systems and installations to burn to ashes. A lot of people have experienced electric shocks, and some have died from electrocution as a result of incorrect grounding of electrical installations [16, 17]. Some structures or buildings are not even grounded since the owners did not perceive the necessity to do so or, possibly in an effort to save money, they removed the building's grounding design from the budget [18-20]. An effective grounding system ensures a safe path between an electrical system and the ground for the discharge of electrical faults.

Grounding of lightning strikes and maintaining the proper operation of electrical equipment requires knowledge of soil resistivity [21-23]. It is a measure of the grounding system quality [24-26]. A grounding network with sufficiently low soil resistivity ensures the safety of the equipment and people around the installation is guaranteed [11, 27, 28]. Hence, the need for soil resistivity measurement prior to the implementation of electrical installations becomes evident. The resistivity of the soil in which a ground electrode is driven has a major impact on the electrode's resistance; as a result, soil resistivity measurements are important consideration when constructing grounding installations [29-31].

Many power system engineers and researchers have conducted several investigations on factors affecting soil resistivity for optimal grounding system performance. Examined in [5] is the effect of some chemical and physical components on apparent resistivity of soil surfaces. The study identified moisture as a significant factor that is directly related to temperature among the numerous overlapping physical and chemical factors that affect soil apparent resistivity. In [18], a review on the effects of non-homogeneous soil characteristics on substation grounding grid performance was presented. The work indicated that the current standards for grounding system design are typically based on homogeneous soil conditions. The enhancement of substation's earthing system via salt, charcoal and water application was investigated in [32]. The research recommended salt, charcoal and water mixture as suitable additive for reducing soil resistivity. Various soil resistivity measurement and interpretation techniques were the subject of the study reported in [33] where it was submitted that ground resistance and ground potential rise were functions of low soil layer resistivity. Assessment of the effect of the soil electrical resistance was carried out in [34] and it was concluded that the quantity of dissolved salts dictated the soil hardness and hence, its resistivity.

X-raying the surveyed literature, some insightful information about factors affecting soil resistivity and how the resistivity could be improved were provided. However, to the best of knowledge of the authors, information on the quantitative modelling of the relationship between soil resistivity and factors such as depth, temperature and moisture content of the soil in the context of grounding is still scanty in literature. Therefore, in this study, the effect of the four factors including depth, temperature, soil size and moisture content on the soil resistivity was assessed and modelled for rainy and dry seasons at five different locations in Federal University of Agriculture, Abeokuta (FUNAAB) via multiple regression analysis.

2. Materials and Methods

2.1 Materials

The materials employed for the actualisation of this research comprise sledge hammer, hand-held digger, measuring tape, test electrodes, drying oven, mechanical sieve shaker, general-purpose specific gravity hydrometer, digital thermometer, a top-loading measuring scale, digital timer, stainless steel scoop, corrosion resistant tray, 12 V battery and Herojat Rhomega-smart soil resistivity meter. Some of these materials were used during the field measurement of the soil resistivity at test locations while others were required during the laboratory analysis of the soil samples obtained from the locations for the determination of the moisture content.

2.2 Methodology

2.2.1 Determination of the Soil Resistivity

The soil resistivity (ρ_s) measurement carried out in the study was done based on the Wenner four-electrode method using Herojat Rhomega smart resistivity meter as described in [35] and shown in Plate 1. The Wenner four-electrode method is one of the best methods for determining the resistivity of soil [7, 20].

Plate 1: Electrical resistance measurement setup

This method uses a ground-resistance meter and four probes. At each test location, the probes (electrodes) were inserted into the soil at depths of 0.150, 0.450, 0.756, 1.110 and 1.490 m determined by the meter and over a span of 10 m. The soil resistivity meter, after the set-up had been completed, was turned on and left to run until a stable result was displayed on the meter's screen. The displayed figure was then recorded as the measured soil resistivity measurement for that location.

When the meter was turned on, a current was made to pass between current probes terminals, while the resulting voltage was measured between the voltage probes terminals. The resitance is given by ratio of potential difference (applied voltage) to the current flow [7] and expressed by (1) while the associated resistivity with the value of resistance is obtained using (2):

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

$$\rho_s = \frac{2\pi D_p V}{I} \quad (2)$$

where R is the resistance, V is the voltage across the conductors, I is the current, ρ_s is the soil resistivity, D_p is the distance between the probes.

2.2.2. Determination of the Soil Texture

One of the most crucial aspects of soil is its size. It is otherwise known as particle size and it is usually used to identify the soil types [36, 37]. The classification of soil into clay, silt, sand, and gravel are based on size of the soil particles [32]. Sieve analysis is usually employed for particle size determination of soil particle with a diameter greater than 0.075 mm while hydrometer analysis is used when the grain is smaller than 0.075 mm in diameter [32, 33].

In spite of the frequent usage of sieve analysis, other methods are normally utilised to determine the distribution of grain sizes in finer soil and in this regard, weaved wire sieve with square openings are deployed [32, 33]. The soil texture (ST) analysis in this research was carried out in laboratory. The graduated cylinder setup for particle soil analysis is shown in Plate 2. The steps involved in the analysis are detailed as follows:

Step I: Soil samples from the test location were weighed, dried and then mixed with a known amount of water in different cylinders;

Step II: The soil-water mixture was stirred vigorously to ensure soil particles are thoroughly dispersed in water. Thereafter, cylinders are left undisturbed for about 30 minutes;

Step III: As the particles settle, different layers are formed; indicating different types of soil, and the grain size was then measured;

Step IV: The textural triangle was used to classify the texture of soil.

Plate 2: The graduated cylinder setup for particle soil analysis

2.2.3. Determination of the Soil Moisture Content

The soil moisture content (MC) is a measure of the quantity of water present in the soil. The moisture is contained in the pore spaces between and within soil particles where some air may be present. The soil is said to be completely dried if its pores contain air only whereas it is said to be saturated if the pores contain water only [23, 34, 38]. The determination of moisture content in this work was carried out via laboratory analysis and the steps involved are detailed as follows:

Step I: The aluminium dishes were weighed;

Step II: 50 g of damped soil from the test locations was divided equally for 10 aluminium dishes;

Step III: The aluminium dishes with the soil were reweighed;

Step IV: Each of the soil in the aluminium dishes was dried for 24 hours at 105^oC in the oven;

Step V: The dishes were taken out of the oven drying to allow for cooling;
Step VI: The dishes with the dried soil were re-weighed;
Step VII: The soil moisture content was determined using (3).

$$MC = \frac{m_2 - m_3}{m_3 - m_1} \times 100 \tag{3}$$

where m_1 is mass of dish, m_2 is mass of dish and moist sand and m_3 is mass of dish and dry sand.

Plate 3 shows the process of soil moisture content determination. Since the MC was determined via laboratory procedure, the study assumed that the same MC values for both rainy and dry seasons.

(a) (b) (c)

Plate 3: process of soil moisture content determination (a) digging out for soil sample collection (b) samples of collected soil samples inside polythene bags (c) samples of damped soil

2.2.4. Measurement of the Soil Temperature

The temperature (T) of the soil during the study was measured using thermometer by contact method. The soil T at the different depths of 0.150, 0.450, 0.756, 1.110 and 1.490 m determined by the deployed smart resistivity meter was measured via digging of the soil to different depths.

2.2.5. Modelling of the Relationship between Soil Resistivity and Soil Depth, Temperature and Moisture Content

In order to establish the relationship between the ρ_s, D, T and MC for each test location, a multiple linear regression (MLR) model which relates one dependent variable with multiple independent variables was employed. The MLR relies on several key assumptions, such as linearity, independence, homoscedasticity, normality, and no multicollinearity. The general form of the model is expressed by (4):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k + \in \tag{4}$$

where Y is the dependent variable (soil resistivity 'ρ_s'), X_1, X_2, …, X_k are the independent variables (depth 'D', temperature 'T' and moisture content 'MC'), β_0 is the intercept, β_1, β_2, …, β_k are the coefficients for the independent variables and ϵ is the error term, which represents the difference between the observed and predicted values of Y.

Several statistics can be used to assess the fit of the model; however, this research considered the use of coefficient of determination (R^2): The R^2 gives the proportion of the variance in the dependent variable that is predictable from the independent variables. The research implemented the expression stated in (4) by deploying the statistical package for the social sciences (SPSS) version 21. This was due to its ease of use and reliability.

2.2.6 Test Location

The ρ_s measurements in this study were carried out at five different locations in Federal University of Agriculture, Abeokuta, Ogun State, Nigeria, as a case study. The site information of the locations which are College of Engineering (COLENG), College of Veterinary Medicine (COLVET), College of Plant Science (COLPLANT), College of Biological Sciences (COLBIOS) and College of Physical Sciences (COLPHYS) is provided in Table 1. The measurements of the ρ_s at the locations were conducted in two different seasons which are rainy season (July 2023) and dry season (January 2024) to examine the trends in the measurements.

Table 1: Site information of the test locations in FUNAAB

S/No	Location	Latitude (º)	Longitude (º)
1	COLENG	07.2301	03.4345
2	COLVET	07.2354	03.4386
3	COLPLANT	07.2326	03.4380
4	COLBIOS	07.2287	03.4358
5	COLPHYS	07.2245	03.4344

3. Results and Discussion

The results of the measured ρ_s at COLENG, COLVET, COLPLANT, COLBIOS and COLPHYS during the rainy and dry seasons over the study period are presented in Tables 1 to 5. Entries of Table 1 revealed that during the rainy season, COLENG exhibited significant subsurface heterogeneity with varying ρ_s values correlating with changes in ST, MC and T. It also displayed a layered subsurface structure with higher resistivity near the surface during the dry season which was likely due to dry soil or rock. Lower resistivity values were observed at greater values of D. This suggests the availability of materials with increased moisture content and low temperature that aided the conductivity of the soil at these D values.

COLVET results as presented in Table 2 displayed heterogeneity with varying ρ_s values likely caused by varying MC, ST and T during the rainy and dry seasons. The upper layer at COLVET exhibited a high ρ_s value while the lower layer showed a low ρ_s value; an indication of the presence of materials with water-saturated zones and low temperature.

Tables 3, 4 and 5 revealed that during both rainy and dry seasons COLPLANT, COLBIOS and COLPHYS, respectively, exhibited heterogeneity with varying ρ_s values relative to changes in ST, MC and T. An increase in resistivity value before ultimate decline was observed with an increase in D. At this point, the soil characteristics changed as the D increases. High resistivity zones were indications of dry, compact materials, while low resistivity zones indicated more conductive zones.

Generally, based on the results shown in Tables 1 to 5, the ρ_s of the test locations was observed to be influenced not only by the D but also ST, MC and T. It was further observed from Tables 1 to 5 that the ρ_s values during the dry season at COLENG, COLVET, COLPLANT, COLBIOS and COLPHYS were higher than the values recorded during the rainy season. This is possibly due to the dryness of various soil substrates or alteration in the soil characteristics that would have aided the conductivity of the soil. Therefore, the distinct resistivity anomalies observed suggest heterogeneity in subsurface materials, which could be due to varying soil types, MC or geological features.

The results of the MLR analysis to quantitatively establish the relationship between ρ_s, D, MC and T for both rainy and dry seasons are presented in Tables 6 to 10 for COLENG, COLVET, COLPLANT, COLBIOS and COLPHYS respectively while the developed models are provided in Table 11. The overall assessment of the results in Tables 6 to 10 revealed that the contribution of the three predictors-D, MC and T to the ρ_s values at the test locations is better due higher value of the multiple coefficient of determination (R^2_{mult}) compared to the individual predictors with lower R^2_{ind} value. Hence, the combined D, MC and T appreciably influence the ρ_s better than D, MC and T considered singly.

Table 1: Measurement of soil resistivity versus soil depth, moisture content and temperature at COLENG for rainy and dry seasons

Depth D(m)	Soil Textural Class	Soil Moisture Content MC(%)	Rainy Season		Dry Season	
			Tempe-rature T(ºC)	Average Soil Resistivity ρ_s (Ωm)	Tempe-rature T(ºC)	Average Soil Resistivity ρ_s(Ωm)
0.150	Sandy clay loam	9.6	31	36.3	40	462.5
0.450	Sandy loam	9.6	30	176.5	40	390.0
0.765	Sandy loam	10.8	30	262.0	39	193.2
1.110	Sandy clay loam	20.3	28	80.1	39	123.7
1.490	Sandy clay loam	20.3	28	31.6	39	123.7

Table 2: Measurement of soil resistivity versus soil depth, moisture content and temperature at COLVET for rainy and dry seasons

Depth D(m)	Soil Textural Class	Soil Moisture Content MC(%)	Rainy Season		Dry Season	
			Tempe-rature T(ºC)	Average Soil Resistivity ρ_s (Ωm)	Tempe-rature T(ºC)	Average Soil Resistivity ρ_s (Ωm)
0.150	Loamy sand	17.6	29	162.5	38	656.5
0.450	Sandy loam	12.3	29	177.5	38	555.0
0.765	Sandy loam	12.7	29	177.5	37	421.0
1.110	Sandy loam	12.2	28	145.5	37	165.5
1.490	Sandy loam	14.2	28	122.0	37	140.0

Table 3: Measurement of soil resistivity versus soil depth, moisture content and temperature at COLPLANT for rainy and dry seasons

Depth D(m)	Soil Textural Class	Soil Moisture Content MC(%)	Rainy Season		Dry Season	
			Tempe-rature T(ºC)	Average Soil Resistivity ρ_s (Ωm)	Tempe-rature T(ºC)	Average Soil Resistivity ρ_s (Ωm)
0.150	Loamy sand	12.0	30	190.0	39	488.5
0.450	Sandy loam	11.6	30	279.5	38	716.5
0.765	Loamy sand	11.3	30	341.5	38	853.0
1.110	Sandy loam	10.1	29	341.5	38	674.5
1.490	Sandy loam	10.7	29	297.5	38	320.5

Table 4: Measurement of soil resistivity versus soil depth, moisture content and temperature at COLBIOS for rainy and dry seasons

Depth D(m)	Soil Textural Class	Soil Moisture Content MC(%)	Rainy Season		Dry Season	
			Tempe-rature T(ºC)	Average Soil Resistivity ρ_s (Ωm)	Tempe-rature T(ºC)	Average Soil Resistivity ρ_s (Ωm)
0.150	Sandy loam	14.0	30	96.85	36	365.5
0.450	Sandy loam	13.2	30	107.3	36	308.0
0.765	Loamy sand	14.0	29	116.0	35	237.0

1.110	Loamy sand	13.2	29	101.4	35	156.0
1.490	Sandy loam	15.1	29	84.7	35	92.2

Table 5: Measurement of soil resistivity versus soil depth, moisture content and temperature at COLPHYS for rainy and dry seasons

Depth D(m)	Soil Textural Class	Soil Moisture Content MC(%)	Rainy Season		Dry Season	
			Tempe-rature T(ºC)	Average Soil Resistivity ρ_s (Ωm)	Tempe-rature T(ºC)	Average Soil Resistivity ρ_s (Ωm)
0.150	Loamy sand	12.4	31	182.0	38	852.5
0.450	Loamy sand	2.39	31	222.5	38	1128.5
0.765	Loamy sand	8.9	30	222.5	37	594.5
1.110	Sandy loam	5.2	30	163.0	37	366.5
1.490	Loamy sand	2.8	30	113.7	37	178.5

Table 6: MLR analysis results for COLENG for rainy and dry seasons

Parameter	Rainy Season			Dry Season		
	Coefficient	R^2_{ind}	R^2_{mult}	Coefficient	R^2_{ind}	R^2_{mult}
Constant	4558			-7021.6		
MC(%)	-49.182	0.2556	0.7335	-2.0902	0.68909	0.9837
T(ºC)	-130.77	0.0949		187.39	0.94123	
D(m)	124.19	0.0432		-92.79	0.86996	

Table 7: MLR analysis results for COLVET for rainy and dry seasons

Parameter	Rainy Season			Dry Season		
	Coefficient	R^2_{ind}	R^2_{mult}	Coefficient	R^2_{ind}	R^2_{mult}
Constant	-500.72			-1227.9		
MC(%)	-5.0415	0.0171	0.9763	4.0627	0.22426	0.9543
T(ºC)	26.013	0.8087		49.597	0.74798	
D(m)	-21.04	0.6163		-372.66	0.94838	

Table 8: MLR analysis results for COLPLANT for rainy and dry seasons

Parameter	Rainy Season			Dry Season		
	Coefficient	R^2_{ind}	R^2_{mult}	Coefficient	R^2_{ind}	R^2_{mult}
Constant	-4084.8			19981		
MC(%)	-133.98	0.5582	0.9974	-155.65	0.0049	0.7670
T(ºC)	195.7	0.1875		-449.71	0.1076	
D(m)	94.222	0.4478		-577.8	0.1109	

Table 9: MLR analysis results for COLBIOS for rainy and dry seasons

Parameter	Rainy Season			Dry Season		
	Coefficient	R^2_{ind}	R^2_{mult}	Coefficient	R^2_{ind}	R^2_{mult}
Constant	887.05			-60.348		
MC(%)	-6.9837	0.4017	0.7382	5.078	0.1984	0.9990
T(ºC)	-22.749	0.0041		10.803	0.7510	
D(m)	-25.11	0.2030		-202.94	0.9970	

Table 10: MLR analysis results for COLPHYS for rainy and dry seasons

Parameter	Rainy Season			Dry Season		
	Coefficient	R^2_{ind}	R^2_{mult}	Coefficient	R^2_{ind}	R^2_{mult}
Constant	4775.9			7509.2		
MC(%)	-11.029	0.0711	0.9777	-58.037	0.0339	0.9931
T(°C)	-142.57	0.1859		-151.94	0.7818	
D(m)	-240.8	0.5080		-1052.6	0.7905	

Table 11: Modelled soil resistivity versus soil moisture content, temperature and depth relationship at test locations for rainy and dry seasons

Location	Modelled equation for ρ versus *MC*, *T* and *D* for rainy season	Modelled equation for ρ versus *MC*, *T* and *D* for dry season
COLENG	$\rho_s = 4558 - 49.18MC - 130.77T + 124.19D$	$\rho_s = -7021.6 - 2.09MC + 187.39T - 92.79D$
COLVET	$\rho_s = -500.72 - 5.04MC + 26.01T - 21.04D$	$\rho_s = -1227.9 + 4.06MC + 49.60T - 372.66D$
COLPLANT	$\rho_s = -4084.8 - 133.98MC + 195.7T - 94.22D$	$\rho_s = 19981 - 155.65MC - 449.71T - 577.8D$
COLBIOS	$\rho_s = 887.05 - 6.98MC - 22.75T - 25.11D$	$\rho_s = -60.35 + 5.08MC + 10.80T - 202.94D$
COLPHYS	$\rho_s = 4775.9 - 11.03MC - 142.57T - 240.8D$	$\rho_s = 7509.2 - 58.04MC - 151.94T - 1052.6D$

4. Conclusion

The effective operation of electrical installations, among many other things, relies on a good grounding system design, whose performance is heavily dependent on the resistivity of the soil in the vicinity of the installations. This study assessed the effect of selected factors which are D, ST, T and MC affecting the ρ_s in five different locations in FUNAAB for efficient grounding system performance for both rainy and dry seasons which span from July 2023 to January 2024. Mathematical models were developed to provide quantitative relationship between ρ_s, D, T and MC at the five locations considered which include COLENG, COLVET, COLPLANT, COLBIOS and COLPHYS via MLR analysis for the two seasons.

The ρ_s measurements conducted during the rainy season at the test locations revealed significant variations in MC and resistivity with depth, underscoring the influence of rainfall on subsurface conditions. Conversely, during the dry season, a higher resistivity value was observed compared to the rainy season, due to the reduced water flow to the soil. It was noted that rocky or sandy materials exhibited high resistivity, while water-saturated layers exhibited low resistivity. Another factor worthy of note is the D, and this study showed that at nearly all the locations resistivity decreased with increasing depths. It was further found out that the combined effect of MC, T and D on the ρ_s was more significant than the individual factors with higher value of R^2_{mult} compared to the R^2_{ind} of the predictors. The results of this study are useful guides for grounding installation in FUNAAB and suitable reference points for further research.

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