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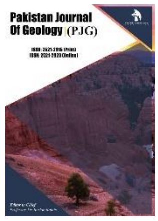

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RESEARCH ARTICLE

INHERENT GEOELECTRIC CHARACTERIZATION FOR TOPSOIL INTEGRITY ANALYSIS IN LOKOJA USING GEOPHYSICAL VES METHOD

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ABSTRACT

This study examines the geoelectric characteristics of topsoil in Lokoja, Nigeria, using Vertical Electrical Sounding (VES) to assess soil competence for engineering structures. Resistivity sounding conducted in the study area identified three main curve types: three-layer (A and K type), four-layer (HA, QH and KH), and five-layer (HAK, HKH and QHA). The top layer resistivity within the study area ranges from 11.7 to 2702.7 ohm-m with thickness ranging from 0.15 to 3.85 m. The depth to basement in the study area ranges from 0.6 m to 49.1m with a mean depth of 15.1 m. The analysis classifies the study area into four competency zones based on resistivity values: incompetent (<100 ohm-m), moderately competent (101–350 ohm-m), competent (351–750 ohm-m), and highly competent (>750 ohm-m). The results indicate that the eastern and northeastern regions, which are dominated by clay, have lower resistivity and present geotechnical difficulties such as differential settlement and soil deformation, while the central and western regions, which are underlain by lateritic and sandy formations, have higher resistivity and are appropriate for construction. Areas with thin overburden and shallow basement rock are further identified by depth-to-bedrock data, which correlates with reduced soil competence. The study provides useful suggestions for reducing geotechnical risks and improving infrastructure resilience in Lokoja, while highlighting the significance of geophysical techniques in urban planning and foundation design.

KEYWORDS

Soil competence, Vertical Electrical Sounding (VES), Geoelectric characterization, Foundation stability, Lokoja-Nigeria

1. INTRODUCTION

Engineering structures are designed for durability, but structural failure can result in severe consequences beyond financial loss, including loss of lives and property. The foundation of any structure is critical to its stability and depends largely on the characteristics of both the structure and the underlying soil or rock. Thus, soil properties play a vital role in ensuring structural integrity, safety, and durability.

Traditionally, civil and building engineers employ geotechnical methods such as the cone penetrometer test to assess the strength of materials supporting infrastructure like roads, buildings, and dams (Rajapakse, 2016). A significant contrast in resistivity often exists between the conductive overburden and the more resistive basement bedrock or lateritic hardpan, aiding in the determination of bedrock depth and subsurface layer identification (Akintorinwa and Abiola, 2011).

Factors contributing to foundation failure include inadequate knowledge of soil and geological materials, poor foundation design, and substandard building materials. These issues can lead to severe structural damage, necessitating thorough soil characterization for effective foundation planning (Ofomola et al., 2018).

Traditional soil competence assessment relies on laboratory testing of soil samples, which is expensive and provides limited point-based data. In contrast, 1D Vertical Electrical Sounding (VES) offers a broader, cost-effective, and non-destructive method for evaluating soil resistivity and lithology, which are then linked to subsoil competence (Idornigie and Olorunfemi, 2006).

VES is particularly effective for subsurface investigations in geological environments with horizontal or near-horizontal layers (Ojekunle et al., 2015; Nwachukwu et al., 2019). It provides rapid data acquisition with minimal environmental impact and reduced interpretational ambiguity (Nwachukwu et al., 2019). This method helps determine lithologic layer thickness and facilitates lithological facies correlation across multiple survey points. Moreover, soil competence, which assesses the ability to withstand stress from overburden pressure, swelling, and anthropogenic activities, is closely linked to the resistivity information provided by VES surveys (Idornigie and Olorunfemi, 2006).

Beyond significant financial losses, structural failure can have severe consequences, including loss of life and property. The cost of rehabilitating failed structures is often substantial, and in many cases, complete redesign and reconstruction are required at an even greater expense (Ayanninuola et al., 2022). Therefore, assessing the competence and stability of earth materials before constructing engineering structures is crucial for preventing structural failure. Proper site evaluation helps mitigate risks associated with inadequate knowledge of soil and subsurface geological conditions, ensuring the integrity and longevity of structures.

Studies have demonstrated that comprehensive information on

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subsurface soil for engineering foundations can be acquired through geotechnical, geophysical methods, or a combination of both (such as in Alabi et al., 2017; Ofomola et al., 2018). Research has been carried out in similar geological environment as the study area using several geophysical methods such as Electrical Resistivity, Very Low Frequency (VLF) Electromagnetics and Seismic Refraction (Falowo, 2018; Ofomola et al. 2018; Mathew et al. 2021; Samuel et al., 2022; Azouko et al., 2023; Ofomola et al., 2018; Alabi et al., 2017; Oluwatimilehin et al., 2023). However, there is insignificant published research output on the subject matter in the present study area.

Our study therefore aims at building on previous research where the electrical resistivity method, particularly VES, has been applied across various geological settings to provide information on the layer resistivity, layer thickness and lithology of the study area. In that way, evaluation of soil competency and categorization of the area into various soil competency zones will be achieved.

A pivotal study on soil competency in Lokoja would be highly significant due to the city's unique geological and environmental conditions. Lokoja, located at the confluence of the Niger and Benue rivers, is characterized by varied soil types, including alluvial deposits, lateritic soils, and basement rock formations. These diverse subsurface conditions can pose challenges to infrastructure development, particularly regarding foundation stability, soil erosion, and susceptibility to settlement or flooding.

Conducting focused research on soil competency in Lokoja would provide critical data for urban planning, civil engineering, and construction projects. Our study would serve as a spring board for more detailed and higher resolution research on the stress bearing capacity of foundational soils within Lokoja. Our study would also help in assessing soil-bearing capacity, identifying potential geotechnical hazards, and recommending appropriate foundation techniques for buildings, roads and bridges. Additionally, such research could mitigate risks associated with structural failures, improve construction cost efficiency, and contribute to the city's long-term infrastructural resilience and sustainability.

1.1 Location and Geology of the Study Area

The study area (Figure 1) is located within Lokoja, and covers approximately 707 km^2. It is situated within the Guinea Savannah climate zone of West Africa, which is characterized by two primary seasons: the wet and dry seasons. Average annual rainfall in Lokoja is approximately 12.14 cm (Olatunde and Isaac, 2018; Naiyeju et al., 2021). The region's average annual temperature typically does not fall below 30.7°C, with February and March being the peak of the hot season (Olatunde and Ukoje, 2016; Naiyeju et al., 2021).

Geologically, the area is underlain by both basement complex and sedimentary formations (Figure 2). The western section is dominated by the crystalline basement complex of Precambrian origin, which includes rocks such as migmatite, migmatitic gneiss, undifferentiated granite, granite gneiss, and biotite hornblende gneiss. In contrast, the eastern section is covered by Cretaceous to Recent sedimentary deposits from the southern Bida Basin, including alluvium, feldspathic sandstone, and siltstone.

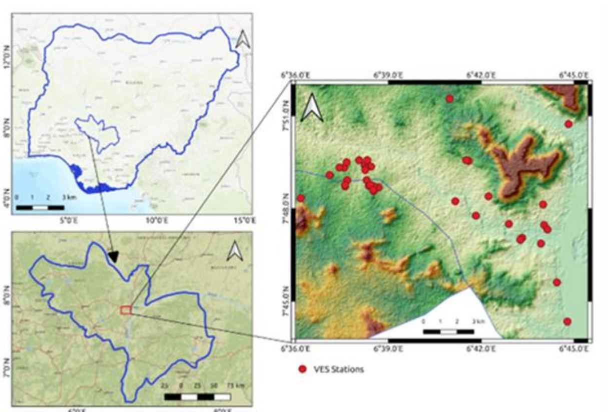

Figure 1: Location of the study Area, showing distribution of VES stations

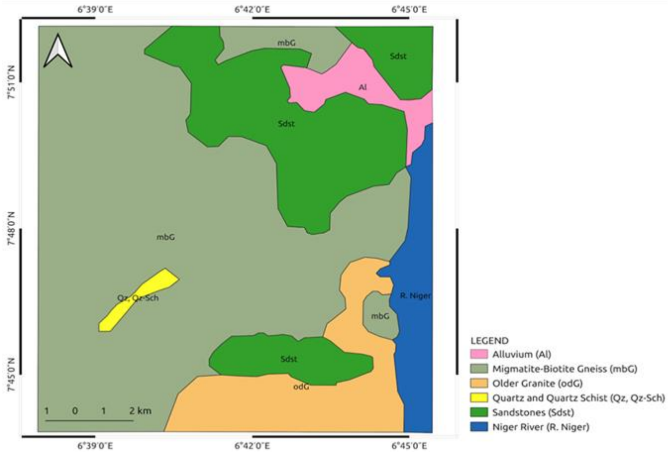

Figure 2: Local geology of the study Area (Modified after NGSA, 2006)

2. Materials And Methods

2.1 Data Acquisition and Processing

Schlumberger electrode configuration was used to acquire Vertical Electrical Sounding (VES) data from thirty-eight (38) stations using SAS 300C Digital Terrameter. Current Electrode separation ranged from 1 m to 120 m, with the Potential Electrode spacing adjusted incrementally between 1 m and 5 m for accurate measurements. Current electrode spacing was gradually increased until the maximum separation was reached, and the electric potential was recorded. Apparent resistivity (ρa) was then calculated using the below equation:

$$\rho_a = \frac{(R*\pi(\text{AB}/2)^2)}{\text{MN}} \quad (1)$$

Where, ρ_a is the apparent resistivity; AB/2 is half-current electrode spacing; R is resistance (R= V/I, with V as voltage and I as current), and MN is potential electrode spacing.

Data processing involved two stages: manual modeling and digital inversion. In the first stage, ρa values were plotted on bi-logarithmic graphs, smoothed, and analyzed with the semi-quantitative auxiliary point method to generate initial models of subsurface layers. In the second stage, these models underwent 1D inversion using WinRESIST software, refining resistivity and thickness values. Results with RMS errors below 5% were accepted; otherwise, the curve-matching process was repeated.

For data interpretation, subsurface lithology and key layers were identified using geological data and borehole logs. Secondary parameters, such as longitudinal conductance, transverse resistance, fracture coefficient, and anisotropy, were derived to create a groundwater suitability map for the study area.

2.2 Secondary Geoelectrical Parameters

The longitudinal conductance (S) and transverse resistance (T) are crucial for current flow parallel and perpendicular to the geoelectrical boundaries, respectively. These parameters, referred to as Dar Zarrouk parameters, are defined for a layer with thickness 'h' and resistivity 'ρ' as follows:

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \quad (2)$$

$$T = \sum_{i=1}^{n} h_i \rho_i \quad (3)$$

When a geoelectrical section involves multiple layers with thicknesses h_1, h_2, h_3, ..., transverse resistances T_1, T_2, T_3, ..., and longitudinal conductances S_1, S_2, S_3, ..., the total longitudinal conductance (S) or total transverse resistance (T) must be taken into account. These are expressed as:

$$S = S_1 + S_2 + S_3 + \cdots S_n \quad \text{where } S_1 = \frac{h_1}{p_1} \text{ and so on} \quad (4)$$

$$T = T_1 + T_2 + T_3 + \cdots T_n \quad \text{where } T_1 = h_1 p_1 \text{ and so on} \quad (5)$$

In areas with homogeneous geoelectric conditions, the parameter S is directly proportional to the depth of the basement, H. Elevated values of S suggest a deeper basement, whereas lower values of S are associated with

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a shallower basement. Consequently, the basement topography is inversely reflected by the distribution of S values.

If the total thickness of the layers in the geoelectrical section is denoted as H, the average longitudinal resistivity, ρ_l, is calculated as:

$$\rho_l = \sum_{i=1}^{n} \frac{H}{S_i} \tag{6}$$

$$\rho_t = \sum_{i=1}^{n} \frac{T_i}{H} \tag{7}$$

It is well established that the resistivity of geological formations is influenced not only by moisture content but also by lithological composition, with grain size being a particularly significant factor in sandy formations. Lithological composition and grain size are veritable controls on the porosity and permeability of rocks and can act as control factors for groundwater recharge potentiality. Additionally, rocks with higher clay content typically exhibit lower resistivity values. The highest resistivity values can be observed for gravels and pebbles, and lowest resistivity are observed for clay formations. A mean value of resistivity for the formation (ρ_m) can be defined as

$$\rho_m = \sqrt{\rho_t \rho_l} \tag{8}$$

2.2 Soil Competency

Soil resistivity correlates well with clay lithology which has been shown to be incompetent for buildings and engineering structures (Ojo et al., 2015; Coker et al., 2015; Bayowa and Olayiwola, 2015). Soil competency has been classified based on layer resistivity and the associated lithology (Idornigie and Olorunfemi, 2006). This soil competency classification and rating is presented on Table 1 below. The competency rating presented on Table 1 was used to reclassify the iso-resistivity map of the top layer of the study area into different competency zones using Inverse Distance Weighting interpolation method in a Q-GIS environment.

Table 1: Soil competency rating by (Idornigie and Olorunfemi, 2006).

Apparent resistivity	Lithology	Competence rating
<100	Clay	Incompetent
100-350	Sandy clay	Moderately incompetent
350-750	Clayey sand	Competent
>750	Sandy/laterite/bedrock	Highly competent

3. Result And Discussion

3.1 Field Curves

Resistivity sounding conducted in the study area identified various curve types classified as: three-layer model curve types (A and K curve-types), four-layer model curve types (HA, QH and KH curve-types), and five-layer model curve types (HAK, HKH and QHA curve-types), some of which are depicted in Figure 3 below. The variability in the curve types reflects the geological diversity typical of complex environments (Akinlalu et al., 2017). This variability is consistent with those obtained in areas with similar geologic conditions with the study region.

The qualitative statistical analysis of the distribution of curve types in the study area indicated that highest occurrence (35.1%) of curve types is the H-type curve, followed by HA (16.2%), and KH and QH curve types with 10.8% occurrence each. The preceding curve types collectively made about 79.4% occurrence in the entire study area. The remaining curve types made up the remaining 21.6%. Of this percentage (21.6%), the 5-layer QHA and HKH curve-types were more dominant, accounting for 50% while K, A, HK and HAK made up the remaining 50%, with equal occurrence.

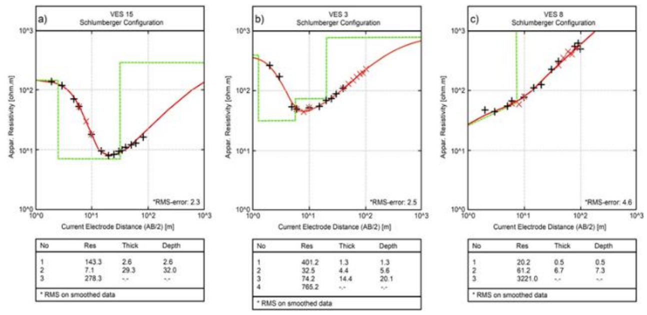

Figure 3: Representative curve types obtained from the study area (a) 3-layer H-type Curve (b) 4-layer HA-type Curve (c) 3-layer A-type Curve. After (Ayua et al., 2024).

3.2 Geoelectric Configuration and Aquifer Model

Three distinct geological models were characterized: the three-layer, four-layer, and five-layer configurations. The three-layer model includes a thin clay topsoil, a weathered basement rock serving as the main aquifer, and an infinite fresh or fractured basement rock below. The four-layer model features a clayey topsoil, alternating clay or laterite layers with varying properties, and a weathered or fractured basement aquifer, underlain by a competent basement rock of indeterminable thickness. The five-layer model starts with a topsoil, lateritic clay, sandy-clay/weathered/ fractured basement complex rocks (aquifer units), and clay/fresh basement complex rocks for the sedimentary and basement portions respectively.

3.3 Overburden Soil Integrity Analysis

3.3.1 Top layer Resistivity

The top layer resistivity within the study area ranges from 11.7 to 2702.7 ohm-m. The soil resistivity values were used to classify the study area into different competence zones. The distribution of resistivity is shown on the classified isoresitivity map (Figure 4). The study area is classified into four competency zones. Incompetent, Moderately competent, Competent and highly competent zones. The competency zones correspond to resistivity as already shown on Table 1 and are associated with varying lithology types.

The incompetent zones have resistivity below 100 ohm-m, corresponding to clay and shale lithology. Moderately competent zones have resistivity ranging from 101 – 150 ohm-m. The lithology of this zone corresponds to sandy-clay-dominant rocks. The competent zones have resistivity ranging from 151 – 350 ohm-m, and are composed of predominantly clayey sands. The final classification is the highly competent zone, with sandy or lateritic lithology or fresh bedrock.

Majority of the study area covering the Central and Western parts of the area have resistivity above 100 ohm-m. This moderate to high resistivity are reflective of sand, laterite and crystalline bedrock which are considered competent subsurface materials due to their high stress resistance (Sheriff, 1991; Olorunfemi et al., 2002). This implies that majority of the study area can be classified as moderate to highly competent zones. This observation is supported by the metamorphic (Archean) lithological rocks found in the central and eastern portions of the study area composed of the migmatite-biotite gneiss basement complex lithology found in the area (Ayua et al., 2024).

Moderately competent and small pockets of incompetent zones are largely found in the northeastern and eastern portions of the study area, corresponding to clay, sandy clay and clayey sand lithology of the the Lokoja Formation. Lokoja formation consists of pebbly clayey grit, coarse-grained cross-bedded sandstone, and occasional thin oolitic ironstone layers (Omali et al., 2011; Ayua et al., 2024). A basal conglomerate composed of well-rounded quartz pebbles embedded in a white clay matrix signifies a fining-upward sequence characteristic of a fluvial depositional environment (Madukwe et al., 2014; Ayua et al., 2024). Exposures of the Lokoja Sandstone at Felele along the Okene-Abuja highway reveal the formation's depositional facies, underlain by claystone units. These claystones exhibit signs of ferruginization and have been linked to hightened corrosion effects in this area, as have been previously reported in literature (Ayua et al., 2024 and references contained therein).

Clay materials tend to deform and flow when subjected to stress, making them geotechnically unsuitable as they contribute to differential settlement in building foundations (Sheriff, 1991). In contrast, sandy clay and clayey sand exhibit varying degrees of load-bearing capacity, classifying them as moderately competent to competent subsurface materials due to their relative resistance to stress. The classification of this area as either incompetent or moderately competent therefore is a consequence of the amount of clay present in the soils.

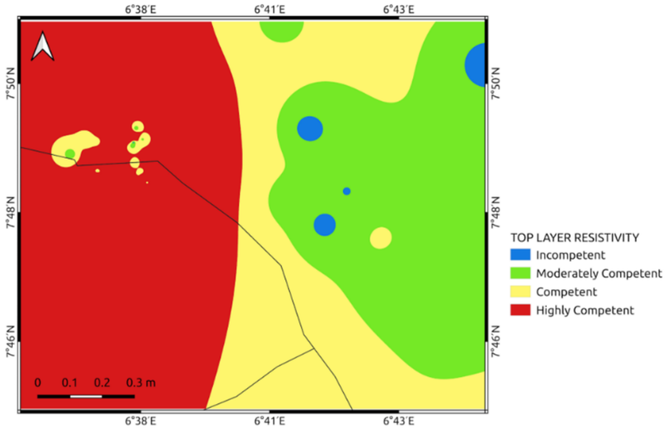

Figure 4: Top-layer competency zonation

3.3.2 Top-Soil Thickness

The top layer thickness of the study area ranges from 0.15 to 3.85 m and the distribution of this thickness is shown on the Top-layer Isopach Map (Figure 5). The top-layer constitutes the layer within which civil engineering structures could be grounded (Bayowa and Olayiwola, 2015). This makes this layer important for consideration of competency analysis for the integrity of structures.

Evaluation of the topsoil thickness in our study area shows that two-thirds of the study area have thickness value ranging between 0.15 and 1.50 m. This was observed in the east, northeast, central and western parts of the area. Areas to the east and north-east, as well as the western parts of the map have top layer thicknesses below 1.0 m. Thickness range of between 1.0 and 1.50 m was observed around the south and southwest, north-northwest, and central portions of the area. The northern and southeastern parts of the area is characterized by highest thickness, ranging from 1.50 to 3.85 m.

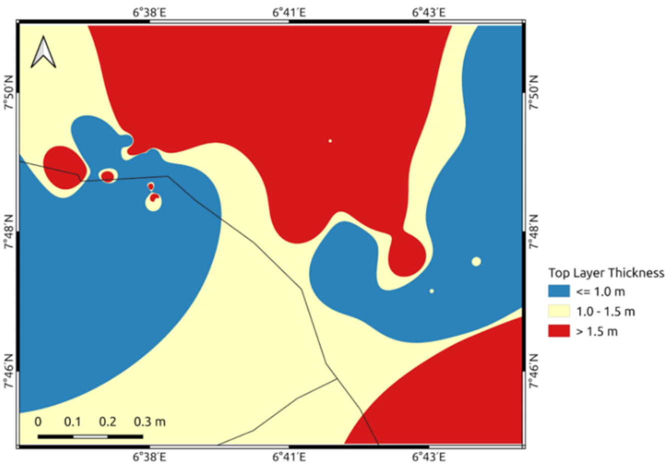

Figure 5: Top-layer isopach map of the study area

Some researchers consider the top-layer as the layer within which engineering structures are grounded (Bayowa and Olayiwola, 2015). On the contrary, others have stated that topsoil is typically regarded as an unsuitable layer for foundation support and should be removed before foundation placement (Olomo, 2023). Consequently, the later group of researchers focused more on assessing the competency of underlying soil layers (Olomo, 2023).

A study in southern Nigeria indicated that the optimal starting depth of 3.0 meters below the surface and a safe bearing capacity of 146.52 kN/m^2 for foundations of circular, square, or strip footings was necessary for erecting structures, and advocated for deeper foundations in parts of their study area for enhanced bearing capacity and enhanced support for structures (Andre-Obayanju and Otoakhia, 2023). In contrast, other studies observed that for most duplexes in Nigeria, where soil bearing capacity exceeds 100 kN/m^2, foundation at shallow depths between 900 mm and 1200 mm are generally sufficient for individual column bases (Ubani, 2021; 2022). Furthermore, other studies from southeastern Nigeria indicated that foundations of buildings should be on lateritic soil with a bearing capacity of 175 kN/m2 and at a depth of one meter (Ubani, 2024). This implies that foundations of buildings need not always be deep but that depth of foundations is dependent upon the bearing capacity of the soils at the location and other factors like the depth of the water table. For instance, when the depth of the water table is very low below the surface, the depth of the foundation is usually kept between 900 mm and 1200 mm (Ubani, 2022). Our study therefore considers both the top layer as well as the entire overburden thickness to constrain the competency of the top layer specifically and the entire sequence of earth material overlying the competent basement.

3.4 Mean formation Resistivity and Depth to Bedrock

Figure 6 (left panel), shows the competency classification of the mean formation resistivity (ρm) of all materials overlying the basement. The competency classification of the mean resistivity of the study area reveals broadly thesame competency classification as the top layer except that the competent zone especially in the western parts of the study area is reduced to a moderately stable classification. This is likely due to lower resistivity materials in the lower stratum as opposed to the lateritic top layers. A large portion of the area is moderately stable with isolated zones of competent areas in the north east, west and north. Pockets of incompetent zones labeled as A, B and C are identified in the west, central and southeastern portions of the study area.

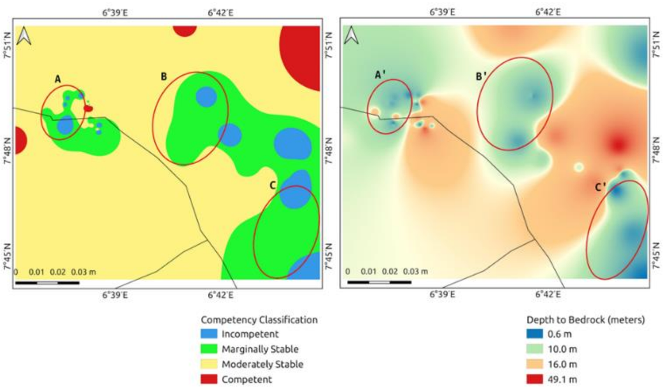

Figure 6: Left: Mean formation Resistivity Map of the study area. Right: Depth to Bedrock

Overburden thickness is defined as the total thickness of all layers extending from the surface to the basement (Ayanninuola et al., 2022). This measurement is determined by aggregating depth-to-basement values for all VES stations and is presented on Figure 6 (right panel). The depth to basement in the study area ranges from 0.6 m to 49.1 m with a mean depth of 15.1 m as shown in the Figure 6. The Eastern, southern parts of the central and northern portion of the area has thick overburden as indicated by brown to red coloration with a thickness ranging from 15.0 to 49.1 m. The overburden thickness map shows three zones of thin overburden thickness generally below 10 m, labeled ass A', B' and C'.

Generally, the foundation depth increases with increasing bearing capacity used for the foundation. For an allowable bearing capacity of 118 kN/m2, a foundation depth of 3000 mm is proposed by Ubani, 2022). Also worthy of mention is that foundations are usually dug in such a way as to avoid too great depths as a depth of about 1500 mm will require supports to keep the sides from caving in, adding to construction costs. Foundations must also be dug above the groundwater level to avoid groundwater control costs and possible instability due to seepage of water into the bottom of the excavation (Ubani, 2022).

The areas with thick overburden indicate high competency while areas with thin overburden indicate low competency. Figure 6 highlight zones A, B, and C as regions of incompetent soils, which align with areas of minimal bedrock depth (A', B', and C'). The findings suggest that the upper 10 meters in these zones are unsuitable for shallow foundation construction. Additionally, has shown that areas with shallow basement rock depths and thin overburden are associated with high static water levels, making them susceptible to excessive settlement beyond tolerable limits, particularly during the rainy season (Falowo, 2018).

The subsoil in the study area, which serves as the foundation for civil structures, primarily consists of sandy clay (marginally stable), clayey sand (moderately stable), and laterite (competent), all exhibiting resistivity values above 100 ohm-m and capable of supporting infrastructure such as roads and buildings (Akintorinwa and Abiola, 2011; Falowo, 2018). Conversely, areas with resistivity below 100 ohm-m typically indicate fractured or faulted zones filled with clay or fluids, rendering them unsuitable for foundation placement. The clayey nature of the weathered layer in many locations further reduces soil competence, as it struggles to withstand stresses from overburden pressure, swelling, and cracking, ultimately compromising structural integrity.

4. Salient Findings And Implications

The study on the inherent geoelectric characterization for topsoil integrity analysis in Lokoja using the geophysical VES method has revealed critical insights into the competence of the subsurface materials. The findings highlight the variations in soil resistivity and topsoil thickness, which are fundamental to understanding the stability and suitability of the soil for engineering structures.

The study classified the study area into four competency zones based on resistivity values: incompetent (<100 ohm-m), moderately competent (101–350 ohm-m), competent (351–750 ohm-m), and highly competent (>750 ohm-m). The central and western parts of the study area exhibit resistivity values above 100 ohm-m, indicating moderate to high competency levels suitable for construction. The northeastern and eastern portions contain significant clay content, resulting in lower resistivity values and geotechnical challenges, such as increased susceptibility to differential settlement and soil deformation.

The topsoil thickness varies from 0.15 to 3.85 meters, with two-thirds of the area exhibiting a thickness range of 0.15–1.50 meters. Areas with thin topsoil (below 1.0 m) correspond to basement rock outcrops, which provide a stable foundation for construction. Regions with greater thicknesses (above 1.5 m) are dominated by clay-rich formations, which can present challenges due to their low bearing capacity and susceptibility to erosion.

Analysis of the mean formation resistivity show three zones A, B, and C of anomalously low resistivity classified as regions of incompetent soils, which align with areas of minimal bedrock depth (A', B', and C'). The findings suggest that the upper 10 meters in these zones are unsuitable for shallow foundation construction and may be associated with high static water levels, making them susceptible to excessive settlement particularly during the rainy season.

The competency of the topsoil correlates strongly with lithological variations. The central and western zones, underlain by lateritic and sandy formations, exhibit higher competency due to their higher stress resistance. The northeastern and eastern zones, dominated by clay, pose higher risks for structural instability due to their deformable nature under load.

The findings underscore the need for targeted foundation design strategies across different zones. Engineering structures in low-resistivity clay zones should incorporate soil improvement techniques, such as compaction and stabilization, to enhance stability. High-resistivity zones present optimal locations for heavy construction, reducing the need for extensive ground reinforcement measures.

5. Conclusion

The study has successfully provided a comprehensive geoelectric characterization of the topsoil integrity in Lokoja, delineating zones of varying competence based on resistivity and lithological parameters. The findings underscore the critical role of geophysical investigations in urban planning and engineering design by identifying areas that require specialized foundation solutions.

Lokoja's central and western sections, predominantly underlain by lateritic and sandy formations, exhibit moderate to high competency, making them suitable for construction with minimal soil treatment. Conversely, the northeastern and eastern portions, with significant clay content, require careful consideration due to their lower resistivity and higher susceptibility to structural failures. These findings align with previous geological and geophysical studies, reinforcing the importance of integrating geoelectric methods in foundational soil assessment.

The study serves as a foundational step toward more detailed and higher-resolution research on the stress-bearing capacity of foundational soils in Lokoja. The results offer practical recommendations for civil engineers, urban planners, and policymakers to enhance infrastructure resilience, mitigate geotechnical hazards, and optimize construction cost efficiency. By adopting these geophysical insights, the structural integrity and longevity of future developments in Lokoja can be significantly improved, ensuring sustainable urban growth and development.

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