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Geoelectric and Geotechnical Soil Characterization at the School of Engineering, Kogi State Polytechnic, Lokoja, Nigeria.

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Abstract
This study examined waterlogging issues at Kogi State Polytechnic, Lokoja, Nigeria, by correlating resistivity measurements with geotechnical data. A 2D dipole-dipole electrical resistivity survey with 5-meter electrode spacing was conducted along three profiles. The data were inverted to interpret subsurface layers. Geotechnical tests, including grain size analysis and Atterberg limits, were interpreted along the profiles to analyze soil properties. The resistivity data identified distinct subsurface layers: the topsoil showed low resistivity between 11.3 and 21.8-Ohm meters, representing loose soils like sand and clay. A second layer (5-8 meters deep) had resistivity values between 20.9–121 Ohm meters, suggesting more compacted materials like clay. The third layer (6-11 meters deep) had resistivity between 60–338 Ohm meters and is interpreted as the weathered basement, while the deepest layer exhibited high resistivity (120–13,918 Ohm meters), indicating solid basement rock. Geotechnical tests revealed the presence of sand, clay, and silt. In addition, they showed varying plasticity and liquid limits: Profile 1 (PL = 26%, LL = 38%), Profile 2 (PL = 52%, LL = 58%), and Profile 3 (PL = 18%, LL = 23%). Profiles 1 and 2 had moderate plasticity, while Profile 3 had a much lower plasticity index of 5%. The inference from these results is that waterlogging is mainly due to prolonged wet seasons. However, if rainfall persists, the presence of clay and silt makes lithology a key factor. Ongoing monitoring and multidisciplinary research efforts are essential for refining the current understanding of the waterlogging process.

Keywords: Water-logging, Rainfall, Dipole-dipole, Resistivity, Lokoja, Soil

Introduction

Water-logging problems are a global environmental issue, arising from the soil's poor water absorption capacity or human activities that impede surface water absorption. These cause water to accumulate on the surface (Bowonder *et al*., 1986; Rinkesh, 2020). Addressing these environmental challenges requires understanding sub-soil characteristics and mechanisms governing water infiltration across various shallow soil layers (Holden *et al*., 2009).

Lokoja is a town where River Niger and River Benue meet hence it is called confluence town. The annual rainfall, which occurs within a significant period and is more experienced in August, ranges between 1,200 mm and 1,500 mm (Walter, 1967). It is, therefore, not surprising that the study area shows evidence of several localized waterlogging problems in the rainy seasons. In the past, these have caused cracks to build up within certain structures in the affected areas (Onsachi *et al.*, 2018). Marshy and muddy soil that restricts the movement of people and vehicles is also common.

The understanding of resistivity distribution can be used to provide stratigraphic and soil-based information at the site. It can aid in predicting the depth of vulnerable layers. This is possible because variations in the electrical characteristics of the soil can be used to classify different soil layers. (Milsom and Eriksen, 2013, Adeoye *et al.,* 2024). The dipole-dipole electrical configuration method emerges as one of the best tools for this study. It is frequently employed when mapping both lateral and vertical variations of resistivity values. The benefits of employing a dipole-dipole array include its ability to cover large horizontal distances, depth of investigation, and sensitivity to vertical structures. Various scholars have conducted this type of study with documented success (Singh, 2013; Minar *et al.,* 2013).

On the other hand, geotechnical analysis in water-logged areas can determine the soil's grain size distribution, which can be used for classifying and validating the different soil types predicted by the resistivity method (Ige *et al.*, 2016). The grain size distribution can further provide information on the ability of the soil to support structural loads, as well as its drainage characteristics.

The Atterberg limits, obtained from the grain size distribution, are an important hydrological parameter that is commonly used to evaluate the soil's plasticity and moisture retention capabilities (Roy and Bhalla, 2017). This helps to understand the behavior of the soil under varying moisture conditions. The Plasticity Index (PI), for example, calculated as the difference between the Liquid Limit and Plastic Limit, provides insight into the soil's range of consistency and potential for waterlogging since higher PI values indicate greater plasticity and a higher propensity for water retention (Skempton, 1953). Overall, the geotechnical characterization used in this study aims to provide a detailed understanding of the soil properties at the School of Engineering site.

Through this study, the understanding of the complex interplay of factors contributing to waterlogging conditions in the area is sought, and this will guide stakeholders in addressing water-logging problems while aiding land use management and potentially leveraging waterlogging and drainage congestion for economic activities. Emphasis is placed on the critical need for proactive strategies to mitigate its adverse effects on urban development and overall environmental sustainability.

Location and Geology of the Study Area

The study area is the Kogi State Polytechnic Itakpe Campus, which is located in the Okehi Local Government Area of Kogi State, North Central Nigeria. It lies within latitude 70°39'N 20" to 70°39'N 30" and Longitude 6°21'E 39" to 6°21'E 49". The Itakpe campus of the School of Engineering Kogi State Polytechnic is located northeast of Okene, about 10km along the Okene-Lokoja road (Plate 1) (Onsachi *et al.,* 2018). Plate 2 shows images of some sections of the study area taken after a light rainfall.

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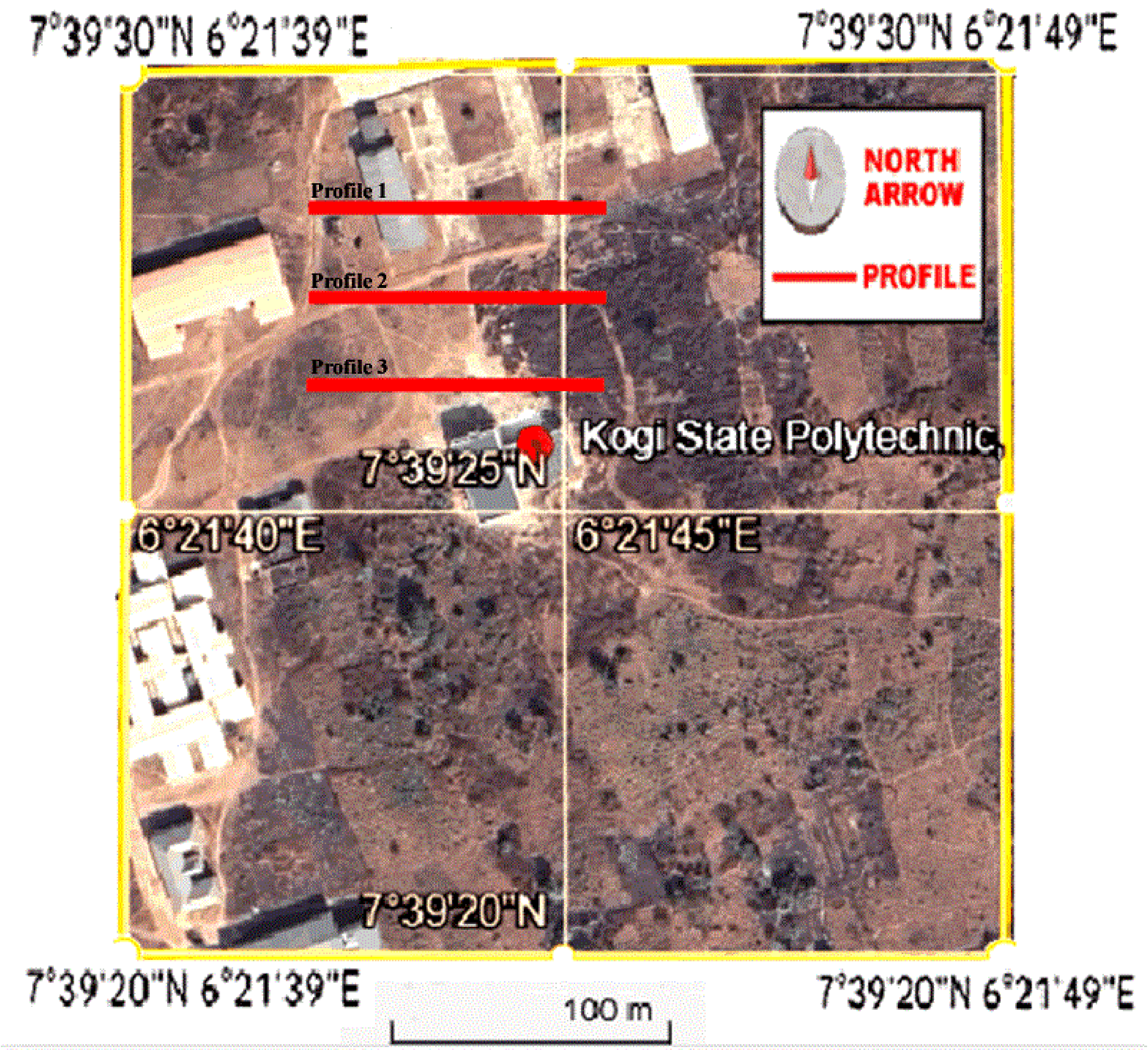

Plate 1: Map of Kogi State Polytechnic showing the data acquisition layout in "red"

Plate 2: Presence of water-logging around the study area

Geology of the Area

The study area is situated on metamorphic rocks like Gneiss, Migmatite Gneiss, and Granite Gneisses, which are usually found in the Basement complex. This complex is part of the PAN African mobile belt in the West African Craton, south of the Tuareg shield (Ajibade *et al*., 1987). Nigeria's basement complex covers North Central Nigeria, South-Western Nigeria, and the Eastern region. It consists of three main groups: the Migmatite gneiss complex, mainly made up of Migmatite and various gneisses; the low-grade sedimentary schist belt; and the granitic rocks that intersect both the Migmatite-gneiss complex and the schist (Ajibade *et al*., 1987).
In terms of precipitation, the research area has both rainy and dry seasons. The rainy season starts in April and lasts until November. The rainy season lasts an average of 217 days, whereas the dry season lasts 151 days, beginning in November and ending in March.

Materials and Methods

Resistivity data were acquired with the ABEM SAS 1000 Terrameter along three profiles using a four-electrode system with a dipole-dipole array configuration. The electrode spacing used was 5m, and the array expansion factor (n) varied between 1 and 5.
Electrical resistivity surveys are based on Ohm's Law, which relates the voltage (V), current (I), and resistance(R):

$$V = IR \qquad \ldots\ldots 1$$

The resistivity (ρ) of the subsurface material is a key parameter that influences the current flow through the subsurface. It is influenced by factors such as lithology, mineral composition, porosity, and salinity (Milsom and Eriksen, 2013). In a homogeneous medium, the resistance (R) is given by the formula:

$$R = p\frac{L}{A} \qquad \ldots\ldots 2$$

Where

R = resistance
ρ = resistivity
L = length of the conductor
A = cross-sectional area

However, in most cases, the subsurface is not homogeneous, meaning that electrical properties vary with depth and lateral position (Adeoye *et al*., 2024). In field measurements, it is essential to calculate the apparent resistivity (ρ_a), which represents an averaged resistivity value influenced by the subsurface properties. The apparent resistivity is derived from the parameters in Equation (1) and is given by:

$$p_a = K\frac{\Delta V}{I} \qquad \ldots\ldots 3$$

Where:

K = geometric factor (depends on electrode spacing)
ΔV = measured voltage difference (V)
I = applied current (A)

The geometric factor K for a dipole-dipole configuration is

$$K = \frac{\pi a n(n+1)(n+2)}{1} \qquad \ldots\ldots 4$$

Where

a = electrode spacing
n = expansion factor

The current was introduced into the subsurface using current dipoles (C1 and C2). The resulting ground voltage along the survey lines was measured by using the potential dipoles (P1 and P2). Both dipoles have the same length (a) (Figure 1).

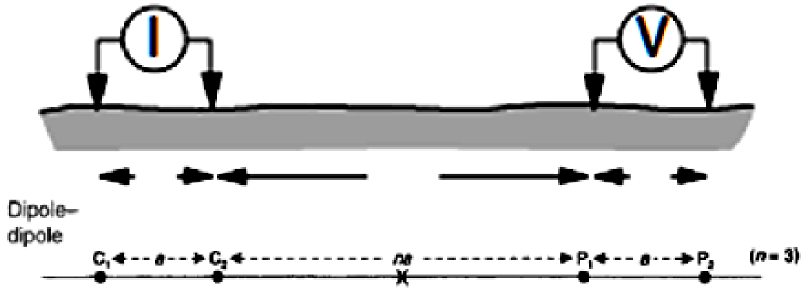

Figure 1: The dipole-dipole field array diagram (Modified from Milsom and Eriksen, 2013)

The apparent resistivity (p_a) distribution obtained by using equation 3 (earlier stated) were inverted using the DIPRO software (Kigam, 2001). Several algorithms for treating the three-dimensional Electrical Resistivity Imaging (ERI) problem have been developed (Dahlin and Loke, 1997; Dahlin and Bernstone, 1997; Spitzer, 1998). The DIPRO software incorporates the smoothness-constrained least squares inversion scheme (Yi *et al*., 2003). Topographic effects were accounted for during inversion by incorporating the topography of the survey area in the resistivity models (Tsourlos and Ogilvy, 1999).

The geotechnical characterization of the school site involved soil sampling and laboratory analysis. These were performed to determine the soil's physical and structural properties. The primary focus was on understanding the soil's grain size distribution, Atterberg limits, and associated engineering properties.

Soil samples were collected along three profiles (1-3) at depths ranging from 2 meters to 5 meters. Samples were obtained using a hand auger and a core sampler.

Grain size distribution was determined by using sieve analysis and hydrometer methods. The sieve analysis was conducted for soil fractions that are coarser than 0.075 mm, while the hydrometer method was used for finer soil fractions since finer soil particles, such as silts and clays, cannot be effectively separated by using sieves. Thus, the analysis helped to classify the soils by using particle size.

The Atterberg limits tests provided insight into the soil's plasticity (Skempton, 1953). The Liquid Limit (LL) and Plastic Limit (PL) were determined using the cone penetration method and the rolling thread method, respectively. The Liquid Limit (LL) test is essential because it determines the moisture content at which the soil transitions from a plastic state to a liquid state. The Plastic Limit (PL) test, on the other hand, is conducted to identify the moisture content at which the soil changes from a plastic state to a semi-solid state.

The Plasticity Index (PI) was calculated as the difference between the Liquid Limit and the Plastic Limit (Eqn 1)

$$PI = LL - PL \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

Where:

PI = Plasticity Index
LL = Liquid Limit
PL = Plastic Limit.

The plasticity index indicates the soil's range of consistency. The greater the PI, the more plastic the soil is.

Results and Discussion

The 2-D pseudo-resistivity sections obtained from the dipole-dipole resistivity measurements along the three profiles revealed subsurface resistivity variations. The variations in resistivity values occur as distinct bands signifying changing subsurface materials and different degrees of compaction or consolidation (George *et al*., 2017).
Figure 2a is the raw field data obtained from the first profile, while Figure 2b is the theoretical pseudo-section obtained from a reasonable model embedded within the software used. Figure 2c, obtained by matching these 2 diagrams, revealed a four-layered earth structure. The topmost layer exhibited resistivity values ranging from 11.3 to 21.8 Ohm meters. Beneath this is a 2nd layer, which was observed between the depths of 5m and 8m with resistivity values ranging from 58.2 to 119 Ohm meters. The 3rd layer has its resistivity range between 120 and 338-Ohm meters and is located between 8m and 11m depth. The deepest layer with resistivity values exceeding 339 Ohm meters was found around 12 meters depth, indicating a more consolidated rock unit (Boobalan and Ramanujam, 2015).
Profile 2 (Figure 3), similarly, showed several bands of resistivity pattern. The first layer had resistivity values between 11.9 ohm-m and 15.8 ohm-m, extending to a depth of 3 meters. The second layer showed resistivity values ranging from 20.9 to 58.8 ohm-m. A third layer, overlying the deepest layer, exhibited resistivity values that range between 60 ohm-m and 118 ohm-m and was observed around 10 meters in depth. The basal rock itself was observed with characteristic very high resistivity values that exceed 120 ohm - m.
Profile three (Figure 4) exhibited similar characteristics to the other profiles. The top layer showed resistivity values ranging from 11.3 to 21.8 Ohm meters, extending to about 3 meters depth. The second layer has resistivity values ranging from 34 to 121 Ohm-m. A third layer, with resistivity values between 210 ohm-m and 219 ohm-m, was found at depths between 6 and 8 meters. The bedrock layer was located at deeper depths, marked by high resistivity values.

Grain size distribution tests indicate a predominance of clayey soils across all profiles. The samples were collected at shallow depths, between 2m and 5m, targeting the topsoil. Sample A, collected along the first Profile, contained 30% sand, 24% silt, and 46% clay (Table 1). Along the second profile, the analysis revealed a predominance of clay and silt, with 60% of the soil classified as clayey, while the remaining 40% comprised sand and a minimal fraction of silt. On the third profile, Sample C showed a similar distribution with clay, again taking the greater percentage at an average value of 43%. However, a moderate presence of sand and silt was also observed. Overall, the soil samples were predominantly clayey, with varying amounts of sand and silt across the profiles.

The Plastic Limit (PL) values offered further insights into the characteristics of the soil samples (Table 2). PL is particularly significant in clay sediments as it defines their ability to transition from a plastic state to a semi-solid state (Dolinar *et al*., 2007). On Profile 1, the PL ranged from 22% to 30%, with an average value of 26%. Profile 2 exhibited a higher PL range of 47% to 55%, with an average of

52%, while Profile 3 had an average value of 18%.

The Liquid Limit (LL) test plot (Fig. 5) shows water content on the vertical axis and the number of blows (N) on the horizontal axis to illustrate the soil's consistency to changes under applied blows. The LL for Profile 1 was observed to be 38%, while Profile 2 (Fig. 6) had an average LL of 58%. Profile 3 (Fig. 7) yielded an LL value of 23%, which was significantly lower than the first two profiles.

The most critical ranking index for characterizing these soils, potentially surpassing the assumptions based on PL and LL, is the Plasticity Index (PI), which is determined by subtracting the PL from the LL (Ige *et al*., 2016). The PI for Profile 1 indicates moderate plasticity at 12%. In contrast, Profile 2 had a PI value of 6%, suggesting a lower degree of plasticity. Profile 3 had a PI of 5%, which corresponds to low plasticity.

In Profile 1 (Figure 2), the resistivity range of 11.3 to 21.8 Ohm meters of the topsoil, which extends to a depth of approximately 3 meters, is typical of loose sands and fine-grained materials like clay or silty soils (Raji and Adeoye, 2017). These soils tend to exhibit low electrical resistivity compared to coarser, drier soils (Milsom and Eriksen, 2013). The transition to a higher resistivity of 58.2 to 119 Ohm meters observed at depths between 5 and 8 meters suggests the onset of a more compacted layer, and the resistivity ranges are typical of clay soil. Below the second layer, resistivity values in the range of 120-338 ohm-meters suggest a consolidated rock unit or a highly weathered bedrock layer. This contrasts sharply with the resistivity of the underlying rock, which has values greater than 339 Ohm meters and reaching up to 13,819 Ohm meters, typical of the basement complex rocks of Nigeria (Adeoye *et al*., 2024).

Profile 2 (Figure 3) presents a similar interpretation pattern. The low resistivity values in the first layer, ranging from 11.9 to 15.8 Ohm meters, again suggest the presence of conductive soils like sand and clay. The second layer, characterized by resistivity values of 20.9 to 58.8 Ohm meters, is interpreted as clay. Below this, the third layer exhibits resistivity values ranging from 60 to 118 ohm-meters, suggesting a shift to more compacted or weathered rock units. Very high resistivity values of the underlying layer confirm the presence of the bedrock layer, which is significantly more resistive than the overlying soils.

In Profile 3 (Figure 4), the resistivity data again agrees with the pattern observed in the previous profiles. The top layer, with resistivity values between 11.3 and 21.8-Ohm meters, is likely a mix of sand and clay. The second layer, with resistivity values ranging from 34 to 121 Ohm meters, corresponds to clay, which is typically more moisture-retentive and exhibits higher resistivity than sandy soils. A third layer with resistivity values between 210 and 219-Ohm meters, observed at depths between 6 and 8 meters, represents a weathered zone that might have a higher porosity compared to the underlying bedrock. As in the other profiles, the bedrock is characterized by very high resistivity.

The consistent presence of low resistivity values in the shallow subsurface layers across all profiles indicates that the surface soils are likely composed of sandy to clayey materials that are either water-saturated or prone to retaining water. The increase in resistivity values in the second layer, which leads to its classification as clay, is noteworthy because clay, due to its fine particle size and plate-like structure, has a high water-holding capacity, making it prone to waterlogging (Romero *et al*. 2011).

The variability in plastic limit (PL) values indicates differences in soil compaction and composition across the study area. From a geotechnical standpoint, the PL value of 26% obtained from Profile 1 suggests that the transition from the plastic to a semi-solid state occurs at a relatively low moisture content. This behavior is characteristic of soils with moderate plasticity, such as a mixture of clay and silt (George *et al*., 2017). Therefore, grain size analysis and PL studies corroborated the resistivity findings along profile one. In addition, silt is confirmed as a major aggregate of the topsoil along the profile.

Profile 2 exhibits a significantly higher PL of 52%, which suggests that the soil in this area may be susceptible to volume change under varying moisture conditions. In addition, the high liquid limit (LL) values for Profiles 1 and 2 (38% and 58%, respectively) indicate that these soils transition into a liquid state quickly if water content increases.

To confirm these assumptions, it was essential to calculate the Plasticity index (PI) from the obtained PL and LL values. Roy and Bhalla (2017) classified soils with PI values above 17% as highly plastic, meaning that they retain large amounts of water (Table 3). In the study, Profile 1 has a PI of 12%, falling within the 7% to 17% (moderate) range. However, given that the study area experiences a prolonged wet season lasting approximately 217 days (Walter, 1967), it is believed that waterlogging is a likely occurrence under excessive rainfall conditions.

For Profile 2, the PI value of 6% suggests moderate clay and silt content. This disclosure means that the soil is moderately plastic and water logging should not be expected except rainfall duration is considerably elongated. In such situations, these soils can undergo volume changes, making them susceptible to swelling. However, the lower PI compared to that of Profile 1 implies slightly better drainage.

Profile 3, with a PI of 5%, indicates a higher proportion of sand or silt relative to clay, which allows better water percolation and reduced water retention. The small difference between Profiles 2 (PI of 6%) and 3 (PI of 5%) suggests only a marginal improvement in drainage. This minor variation implies that significant differences in waterlogging behavior between the two profiles should not be expected.

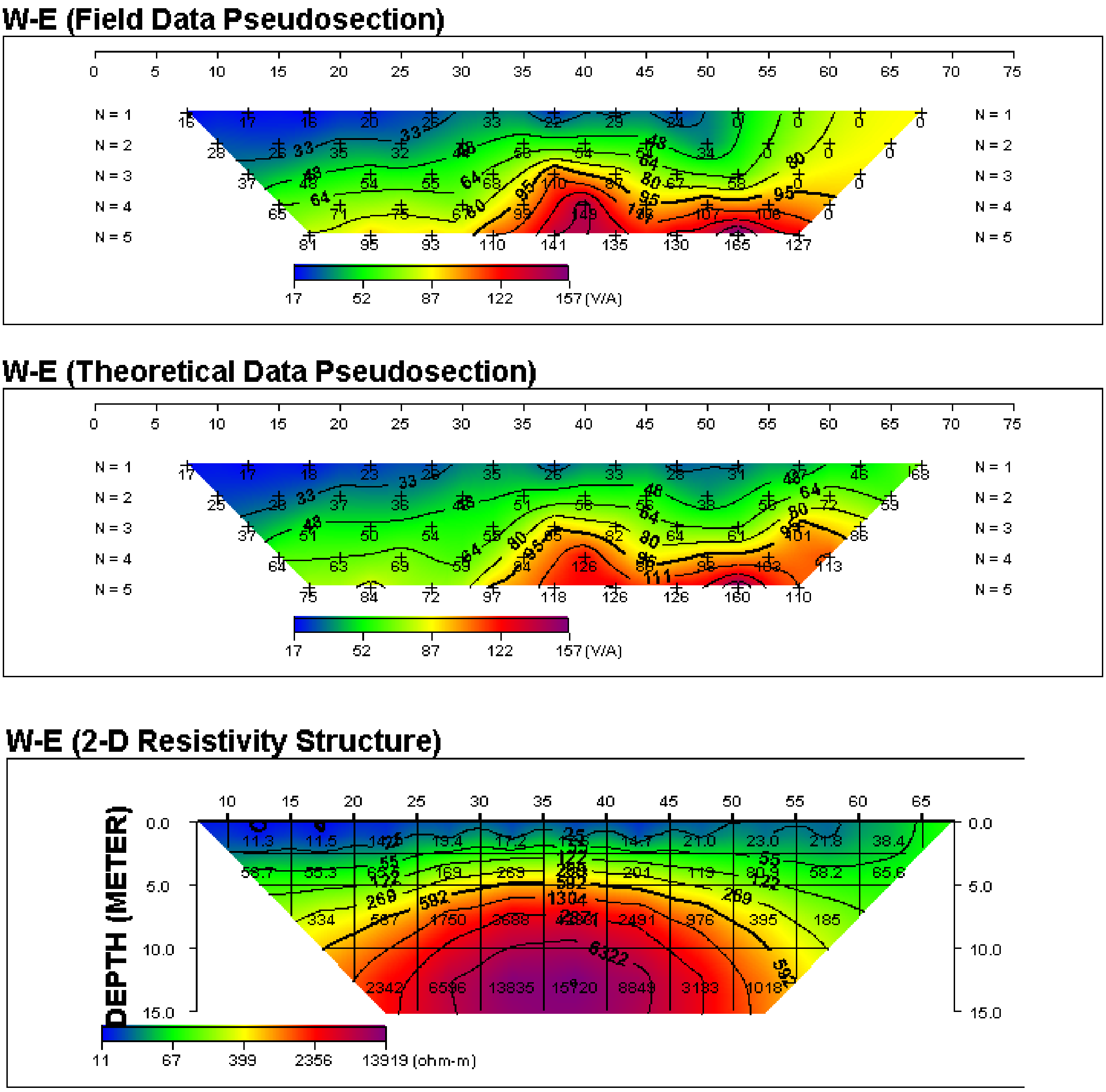

Figure. 2a, b, and c: Resistivity sections of the raw field data, theoretical data, and inverse model observed along the first profile.

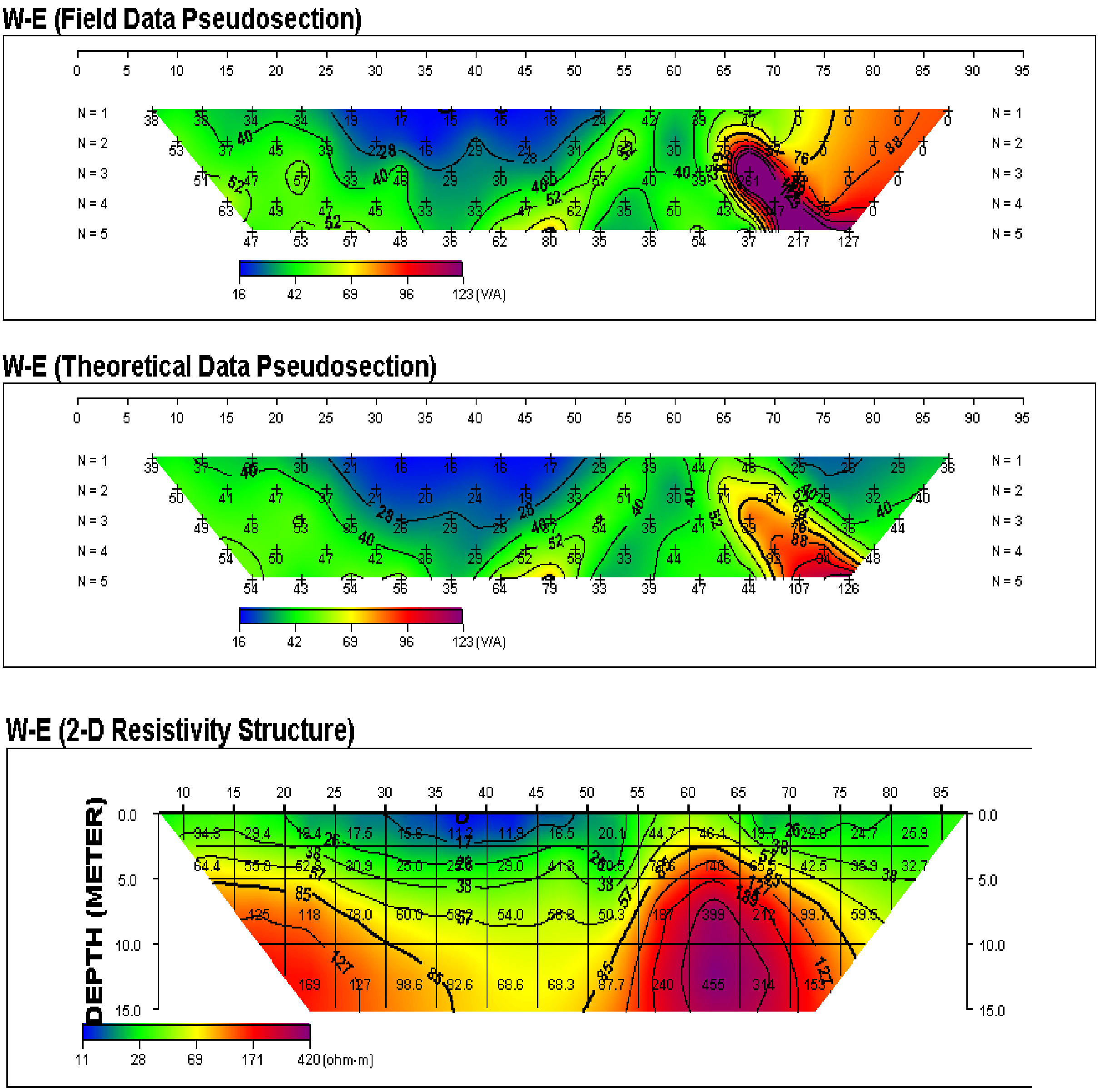

Fig. 3a, b, and c: Resistivity sections of the raw field data, theoretical data, and inverse model observed along the second profile.

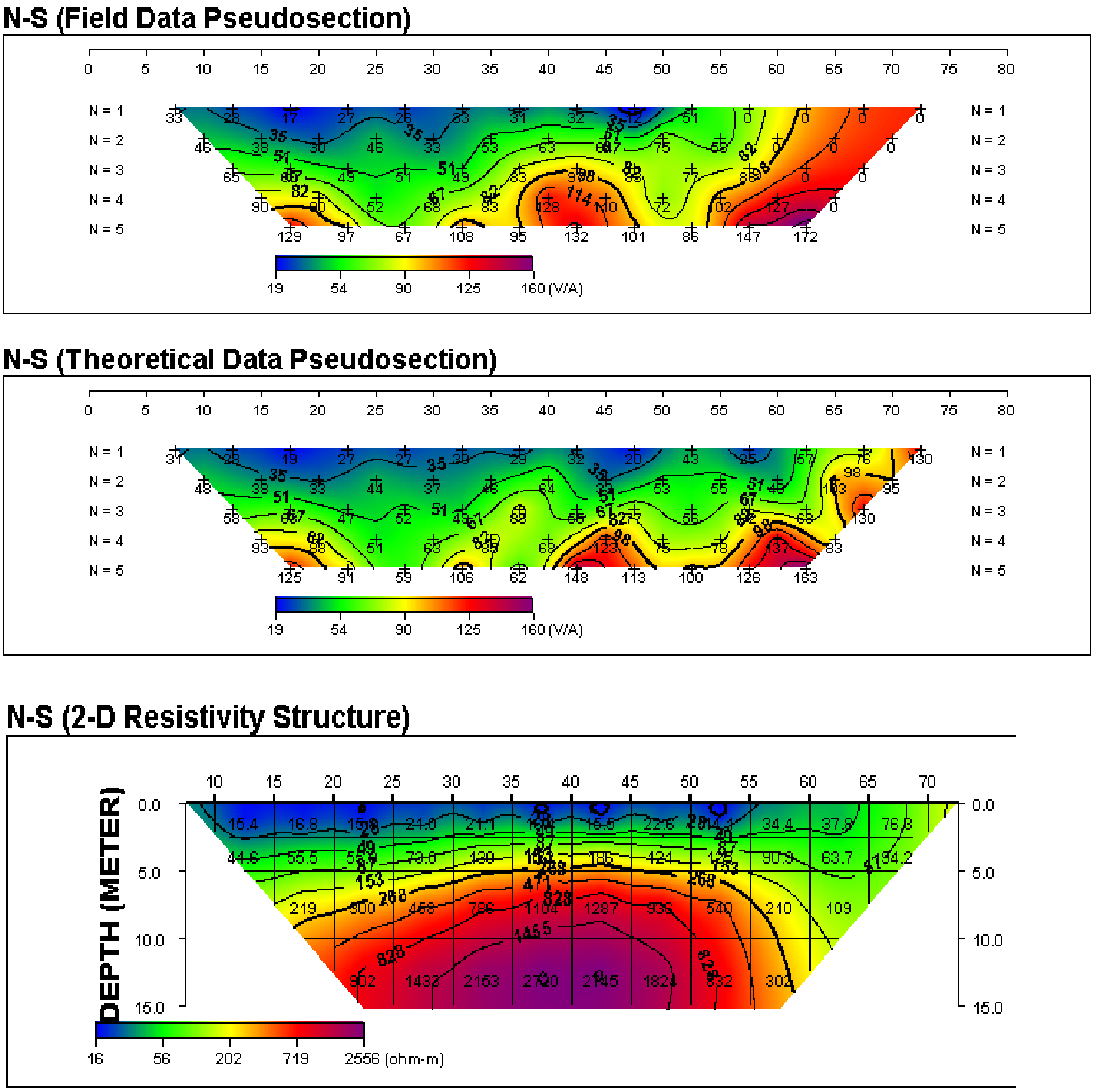

Fig. 4a, b, and c: Resistivity sections of the raw field data, theoretical data, and inverse model observed along the third profile.

Table 1: Summary of grain size analysis of the studied soil samples

Samples	Percentage		
	Sand	Silt	Clay
Sample A (Profile 1)	30%	24%	46%
Sample B (Profile 2)	22%	18%	60%
Sample C (Profile 3)	29%	28%	43%

Table 2: Plastic limit analysis of the studied soil samples

Profile	Distance (m)	Sample ID	Plastic Limit (%)
1	10	A	26%
2	50	B	52%
3	10	C	18%

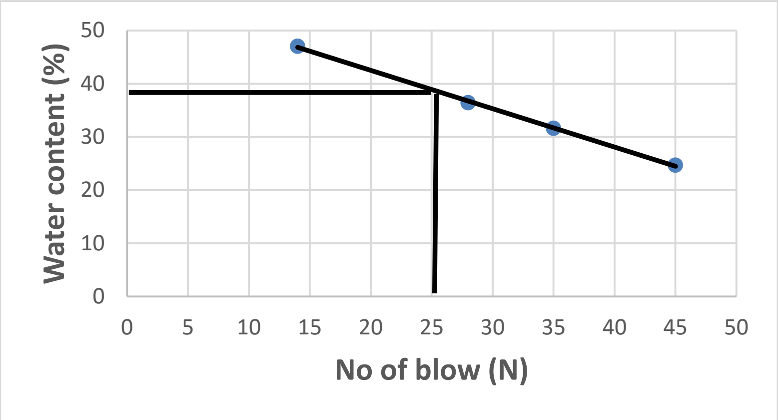

Figure 5. Sample plot for the liquid limit test using the Casagrande cup method obtained along Profile 1.

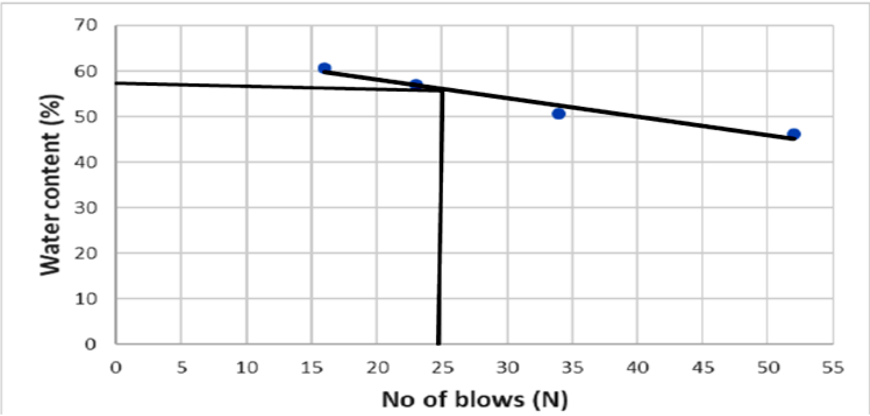

Figure 6. Sample plot for the liquid limit test using the Casagrande cup method obtained along Profile 2.

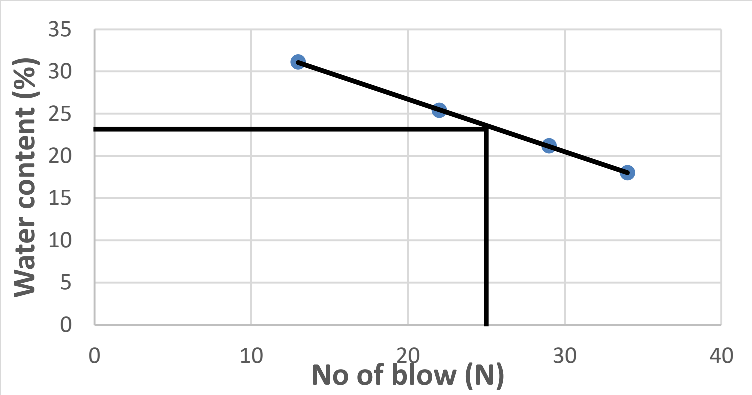

Figure 7. Sample plot for the liquid limit test using the Casagrande cup method obtained along Profile 3.

Table 3: Table showing types of soils based on plasticity index (Adapted from Roy and Bhalla, 2017).

Plasticity Index (%)	Soil type	Degree of Plasticity	Degree of Cohesiveness
0	Sand	Non- plastic	Non-cohesiveness
<7	Silt	Low plastic	Partly cohesive
7-17	Silt clay	Medium Plastic	Cohesive
>17	Clay	High plastic	Cohesive

Conclusion

The water retention capacity of soils has been studied at Kogi State Polytechnic by using geoelectric and geotechnical characterizations.

The 2-D resistivity section revealed notable variations in near-surface resistivity values. A shallow 4-layer geo-electric model was identified beginning with a top layer which is interpreted from resistivity indication as a mixture of sand and clay with resistivity ranging from 11.3 to 21.8 Ohm meter. This layer was observed at an average depth of 4m. Beneath this was a clay layer with moderate resistivity values ranging from 20.9 to 121 Ohm meter, located at an average depth of 5m to 8m. The third layer was interpreted as the weathered basement with resistivity values observed from 60 to 338 Ohm meter. Finally, a fairly competent layer was found around 12m below the surface, with high resistivity values that range between 120 and 13,918-Ohm meter.

While the resistivity analysis has been able to identify sand, clay, weathered basement, and basement layers, the geotechnical analysis revealed that at shallow depths, silt is also present. There are varying soil compositions across the three profiles at these shallow depths, with Profile 1 showing a mixed composition of 30% sand, 24% silt, and 46% clay. Profile 2 exhibited a predominance of clay. However, it also contains moderate amounts of sand and silt. Profile 3 also revealed a mixture of sand, silt, and clay. Although resistivity, PL, and LL analyses suggest that significant clay and silt are present, the plasticity index (PI) indicates that clay's role becomes significant only during prolonged rainfall. This is because all profiles fall within the moderate plasticity range, according to Roy and Bhalla's 2017 classification. The geotechnical results, therefore, indicate that at high rainfall levels, the soils are more susceptible to water retention. The minimal difference in the Plasticity Index between Profiles 2 and 3 suggests that the drainage improvements needed for both profiles may not vary significantly.

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