An Estimation of Soil Geotechnical Parameters Using Electrical Resistivity

by
Nnadozie Onyekachi Ayogu & Raphael Iweanya Maduka
Department of Geology
&
Chinero Nneka Ayogu
(Corresponding author**)**
Department of Geography
University of Nigeria, Nsukka

Abstract

Determination of soil bearing capacity is vital for successful engineering work. The conventional method of obtaining geotechnical properties of soil are time consuming and destructive. In recent times, electrical resistivity has been applied in estimation of soil properties. Due to the fact that it is a time effective, quick and non-destructive method of obtaining soil properties. This study was to investigate the geotechnical properties of soil in Eha-Amufu and its environs using electrical resistivity method of schlumberger configuration array. Electrical resistivity was conducted along the boreholes in the study area of which the soil samples was collected at interval of 3m to the depth of 15m in each of the six boreholes studied. A total of 30 soil samples were collected and sent to laboratory for geotechnical analysis. The result obtained from both the electrical resistivity and laboratory analyses were tested to determine the correlation coefficient (R^2) of these parameters with each other by applying logarithmic, polynomial, exponential, and power curve fitting calculations. The result ranged fromstrong ($R^2 \geq 0.6$), moderately strong ($0.6 \geq R^2 \geq 0.3$) and weak ($R^2 \leq 0.3$) correlations among the tested parameters. Electrical resistivity method, therefore, showed a great possibility of estimating various soil geotechnical properties, and thus can serve as a quick alternative in determining geotechnical characteristics of soils.

Keywords: Electrical resistivity, Geotechnical properties, Correlation, Angle of internal friction, Gravimetric water content

1.0 Introduction

The geotechnical properties of a soil are essential in determining the success of any engineered or natural structures such as building, slope and road (Abdulrahman et al 2022; Roodposhti et al, 2019; Islam et al, 2020). Therefore, there is a need to carry out soil analysis to ascertain the compressibility or consolidation potentials as well as the bearing strength of the soil of a particular site/field (Shah et al, 2022; McCarthy,1977; Una et al,2015). The conventionalmethod of obtaining these geotechnical properties of soil is laboratory test performed on soil samples obtained from construction site/field through well coring/open-pit. However, the process of collecting the sample is generally time-consuming and costly. Equally, properties of soil are normally spatial and temporal variations.Therefore, for a precise determinationof soil properties, high-density sampling will be required. This method of collecting soil sample such as well coring/open-pitwould be a very expensiveand time-consuming operation to carry out in such condition (Islam et al 2020; Pozdnyakova,1999; Siddiqui et al 2012).

In the last decade, the involvement of geophysical methods such as seismic refraction, magnetic, ground penetrating radar, and electrical resistivity, has become a promising approach in characterization of geotechnical properties of soil for engineering construction and hydro-geological project (Adepelumi et al,2009; Adepelumi et al 2000). Due to the fact that they are readily available, cost-effective, and non-invasive (Islam et al 2020; Cosenzaet al 2006; Pozdnyakov et al 2006;Olorunfemi et al,2010; Siddiqui et al,2013). Among these geophysical methods, electrical resistivity survey has been frequently used in delineating and characterization of subsurface properties without disturbance to soil (Islam et al, 2020;Siddiqui et al 2012;Samouelian et al, 2003). During resistivity survey, current is injected into the earth through a pair of currentelectrodes and potential difference is measured between a pair of potential electrodes (Kearey et al,2002). The current and potential electrodes are generally arranged in a linear array. Common arrays include the dipole-dipole, pole-pole, Schlumberger and Werner array.

Lately,geo-electrical resistivity has been deployed in assessment of geotechnical properties of soil, including shear strength, determination of thickness of overburden and subsurface structures (Islam et al 2020;Siddiqui et al,2012). Several researchers have used electrical resistivity in investigating groundwater contamination, aquifer characterization (Selemo et al, 1995; Olayinka et al 2019; Nwankwoala et al 2008; Okogbue et al 2013; Ayogu et al 2021),clay contents (Islam et al 2020; Maduka et al 2016; Gao et al, 2019; Mehmood et al 2020), shear strength, and plasticity index(Islam et al, 2020;Siddiqui et al 2012;Syed et al, 2014). It has also been used to estimate landfill thickness and mapping salt-water intrusion (Pozdnyakov et al, 2006).

Several attempts have been made by many researchers to correlate the soil geotechnical parameters with electrical resistivity and have found a non-linear correlation between electrical resistivity and soil moisture content (Cosenza et al 2006; Pozdnyakov et al, 2006; Schwartz et al 2008; Ozcep et al 2010). However, many reports from other authors have found a strong relationship between electrical resistivity and SPT-N values (Olayinka et al 2019), compressive strength (Liu et al, 2008) and moisture contents (Syed et al. 2014), but a weak correlation with cohesion and angle of internal friction (Syed et al, 2014). Previous investigations into the relationship between electrical resistivity and soil parametersshowed a greater possibility of using in situ electrical resistivity for the prediction of geotechnical properties, but more extensive field tests under different geologic environmental conditions are required to authenticate earlier findings (Islam et al 2020).

This work is necessitated by the need to have a better understanding of the inconsistent and hysteretic nature of relationships between electrical resistivity and various geotechnical properties of soil. It is imperative to investigate these relationships under a variety of geological conditions with soils of different physicochemical and biological properties (Islam et al 2020; Syed et al 2014). It is against the above background that the present studyaims to determine the possibility of using electrical resistivity, a nondestructive andcost-effective method for the estimation of different geotechnical properties(liquid limit, plastic limit, bulk mass density, gravimetric water content, angle of internal friction, cohesion, particle size of foundation soils in Eha-Amufu. The findings of this study would be serving as an alternative quick estimation of different geotechnical properties from the in-situ values of electrical resistivity.

2.0 Study area

2.1 Location and accessibility

Eha-Amufu located in Enugu State, southeastern Nigeria lies within latitude 6°38′ and 6°46′ N and longitudes 7°35′ and 7°38′ E with a relief which ranges between 243meters high to 75meters low (Fig.1). The vegetation of the study area lies within the tropical rain forest region of Nigeria and the climate fall within wet and dry (AW) climate of Koppenclassification. The area experiences two distinct seasons, the rainy and dry. The dry season begins in November and ends in March while rainy season begins from April and ends in October.The total annual rainfall ranges from 2000 to 2500 mm and mean annual temperature range of the study area is 27–28 °C (Monanu, 1975a). The area is moderately humid, about 60–80% (Monanu, 1975b; Iloeje, 1981) and pressure ranges from 1010 to 1012.9 mbar (Monanu, 1975b).

2.2 Geology of study area

The break-up of the south American and African continents in the early Cretaceous lead to formation of southern Nigeria sedimentary basin (Murat, 1972). Various researchers have used geophysical, structural, stratigraphic, and palaeonotologic evidences to support a rift model of the basin (Reyment, 1969; Petters, 1978; Benkhill, 1989; Oyedim et al 2009; Igwesi et al 2013). The development of the Benue Trough through the break-up provided the main structural control and framework for the subsequent geologic evolutionof the region.

The study area lies within the western part of the Lower Benue Trough of Nigeria(Ayogu et al 2021; Reyment, 1969; Petters 1978; Mamah et al 2014).The stratigraphic packaging of the Anambra Basin consists of the Agwu Formation, Nkporo Formation,Mamu Formation (Lower Coal Measure),Ajali Formation and Nsukka Formation (UpperCoal Measure). The formation that outcropped in the study area are AgwuFormation, Npkoro Formation and Owelli Sandstone (Fig.2).TheNkporo Formation consists of Enugu Shale and OwelliSandstone. Agwu Formation which is the major outcrop in the study area is characterized by bluish grey,well-bedded shales with intercalations of fine-grained sandstones and often thin marly shelly limestones(Murat, 1972). The beds are rich in ammonites and other mollusks (Kogbe, 1981). The occurrence of low diversity arenaceous foraminifera in the Awgu Formation indicates deposition in marshy, deltaic, and shallow marine conditions (Una et al,2015; Obaje 1994).

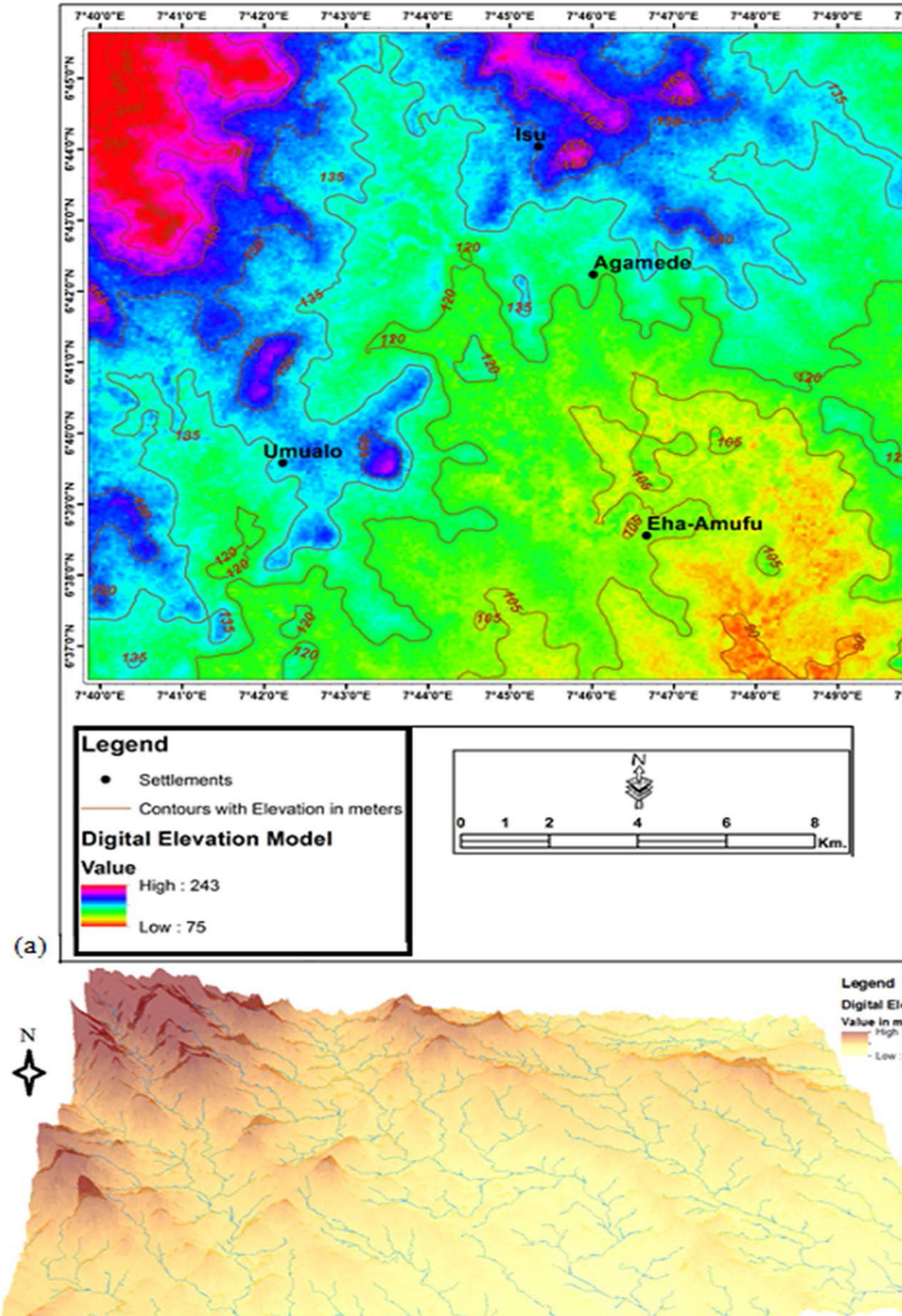
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Fig. 1: The Study Area.

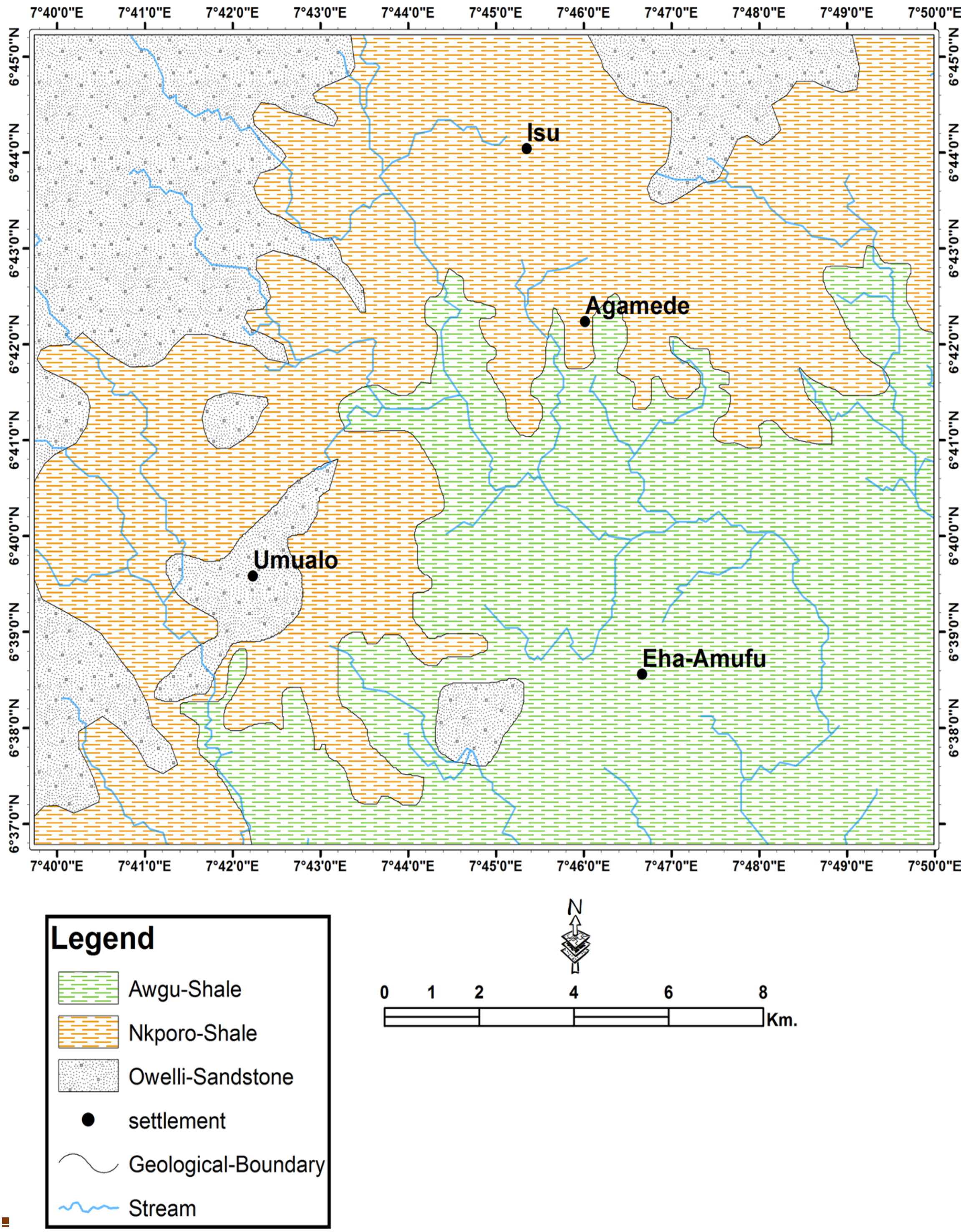
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Fig. 2: Geology of the Study Area.

3.0 Materials and Methods

The study methodology comprises both field and laboratory investigations. Field assessment consists of geophysical survey using vertical electrical sounding (VES), while the laboratory analysis consists of geotechnical parameters of the soil samples. Data analysis involves bivariate plot carried out with MicroSoft Excel worksheet.

3.1 Vertical electrical sounding

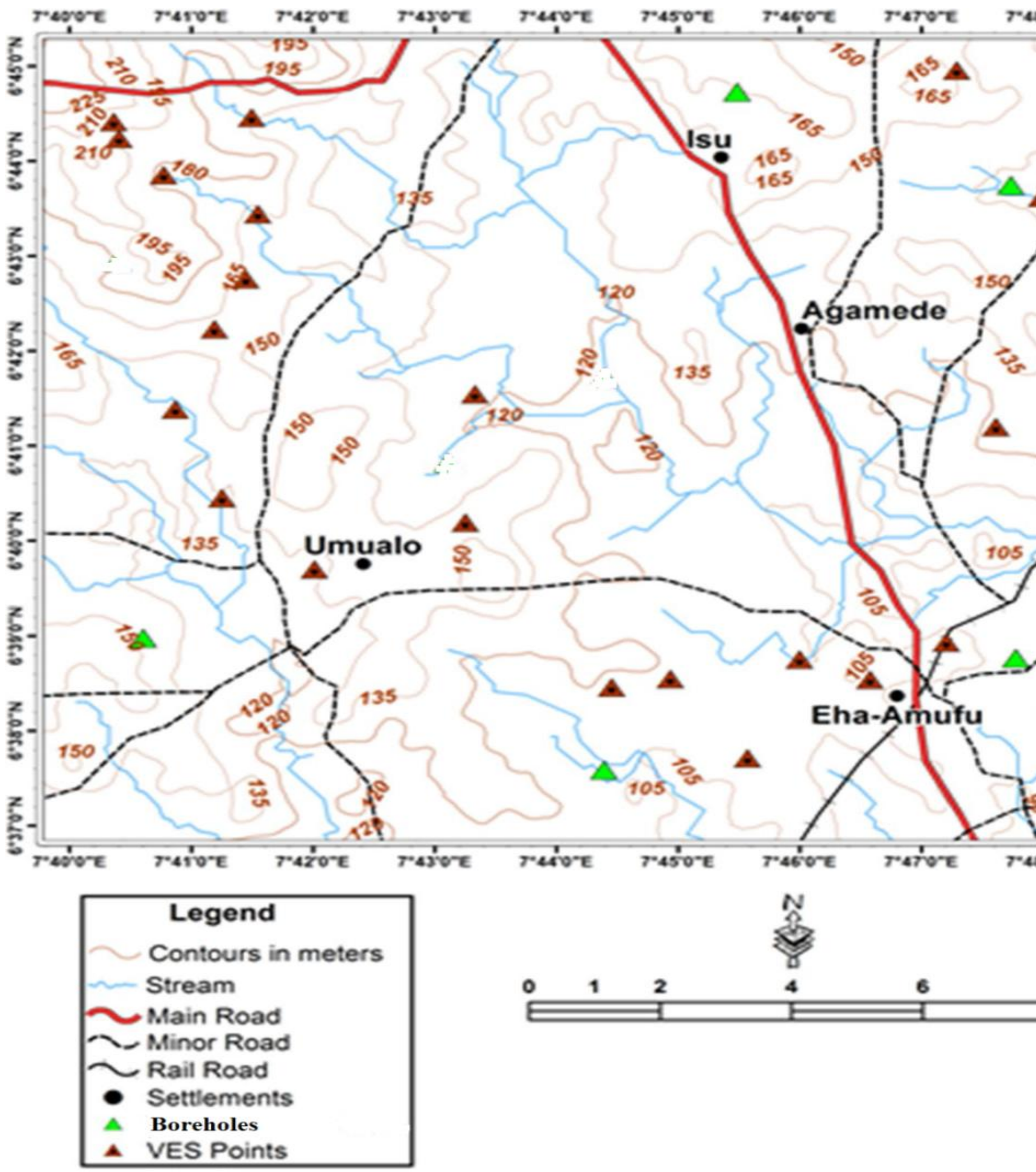
Vertical electrical resistivity (VES) measurements were made along each borehole (BH 1 –BH 6) (Fig.3),to acquire subsurface geo-electric information using ABEM SAS 4000 Terrameter consisting of steel electrodes, current supplying cable, potential measuring cable, dry batteries. The Schlumberger electrode configuration was adopted due to its maximum depth of penetration per unit current electrode spacing. Its high vertical resolution moreover yields good information on subsurface lithology (Atakpo, et al 2009).Schlumberger electrode configuration of a half current electrode spread (AB/2)of 30 m and half potential electrode spacing (MN/2) ranging from 0.5 and15 m was employed. The VES curves were quantitatively interpreted by partial curve matching and computerinteraction techniques based on linear filter theory using 1P12win computer software.

3.2 Laboratory investigation

A total of 30 soil samples were collected from six boreholes (BH 1 – BH 6) at interval of 3m to the depth of 15m. The obtained samples were taken to the laboratory for soil characterization. The following laboratory tests were performed on the soil samples obtained from the boreholesin accordance with the specifications of BSI (British Standard Institution) and ASTM (American Society for Testing and Materials). Parameters investigated in the laboratory were particle size distribution, specific gravity, compaction analysis for maximumdry density and optimum moisture content, undrainedtriaxial compression for the shear strength parameters and Atterberg limits.

3.3 Data analysis

Data obtained both in vertical electrical sounding and geotechnical test were tested for statistical significance using the statistical packages to determine normality. Microsoft Excel has been used by several researchers to calculate the correlation between variables using the least squares regression (Islam et al ,2020; Hatta et al 2015).In correlation analysis, a simple correlation coefficient (R^2) ranging between − 1 and + 1 is estimated.The sign of the correlation coefficient indicates the direction of the correlation while the magnitude of the correlation coefficient indicates the strength of the correlation (Neyamadpour, 2019).



Fig; 3: Sample Stations

The electrical resistivity of the geo-electric layer and the geotechnical properties such as cohesion,angle of internal friction, water content and plasticity of 30 samples obtained from 6 boreholes were tested to determine the correlation of these parameters with each other by testing logarithmic, polynomial, exponential, and power curve fitting calculations.

4.0 Result and discussion

4.1 Soil investigation

A total of 30 soil samples were collected from BH-01 to BH-06 boreholes and subjected to geo-technicalanalysis for various soil parameters which include shear strength, particles size distribution, plasticity index, liquid limit, and natural moisture content. The mean and range of the soil parameters analyzed in the laboratory as well as the sampling depth are presented in Table 1.

The grain-size obtained reveals that 86.4% of the total samples are sandy clay while 13.6% are silty sand according to British Soil Classification System (BSCS). Natural moisture content (NMC) of the soil samples ranged from 6 – 14.83% with average of 10.93% while the liquid limit (LL) ranged between 22 – 58% with an average of 40.5% at the depth of 1 to 3m. The range and mean of NMC and LL at different depth intervals are shown in Table 1. Laboratory result values revealed that the highest and lowest amounts of NMC andLL are within sandy clay and silty sand respectively. It was also found that the plasticity index of most of the samples were above A-line and U-line as presented in Fig 4. From the plasticity chart, the sandy clay has a medium to high plasticity with plasticity index ranging from 20 and 45%. The sandy soils have lower plasticity with index ranging from 0 to 8.5%.

The outcome of the direct shear test revealed that sandy clay samples exhibit higher cohesion and lower friction angle values whereas the silty sands show lower values of cohesion and higher friction angle. This is as result of the amount of clay content present in the samples and the grain size geometry plays a major role on the behavior of soil when subject to sharing tests.

4.2 Vertical Electrical Resistivity (VES)

Vertical electrical resistivity conducted within the study area, revealed three distinct geo-electrical layers which was also confirmed by the sample collected from the boreholes up to 15m depth. The Ipi2win software was employed to interpret and invert the apparent resistivity values acquired during VES survey in the field along the boreholes. The apparent resistivity inversion processproduced sub-surface resistivity of the different layers encountered with their thicknesses. The unsaturated lateritic soil which appeared at the upper layer with a thickness of about lm showed a high resistivity in all boreholes (BH 1 to BH 6) ranging between 800 and 1500Ωm.

Table 1: Geotechnical data of the boreholes at different depths

Sampling depth (m)	Cohesion (kPa)	Internal friction angle (°)	Liquid limit (%)	Plasticity index (%)	Natural water content (%)
1 – 3					
MEAN	22	14	40.5	23.17	10.93
RANGE	13 - 35	9 – 20	22 – 58	9 - 38	6 - 14.83
4- 6					
MEAN	22.5	18.83	44.76	24.5	9.21
RANGE	16 - 33	15 -21	31 -55	11 -31	8.5 - 10.33
7- 9					
MEAN	25.33	15.83	46	25.5	10.85
RANGE	18 -32	11 - 20	24 - 67	1 - 46	6- 12.94
10 – 12					
MEAN	29.66	11.33	52.66	29.5	10.24
RANGE	25 - 35	11 – 13	27 - 76	3 - 46	6.98 -13.89
13 – 15					
MEAN	35.5	16	37.5	29	9.51
RANGE	34 - 37	12 – 20	30 – 45	28 - 30	9.45 - 9.57

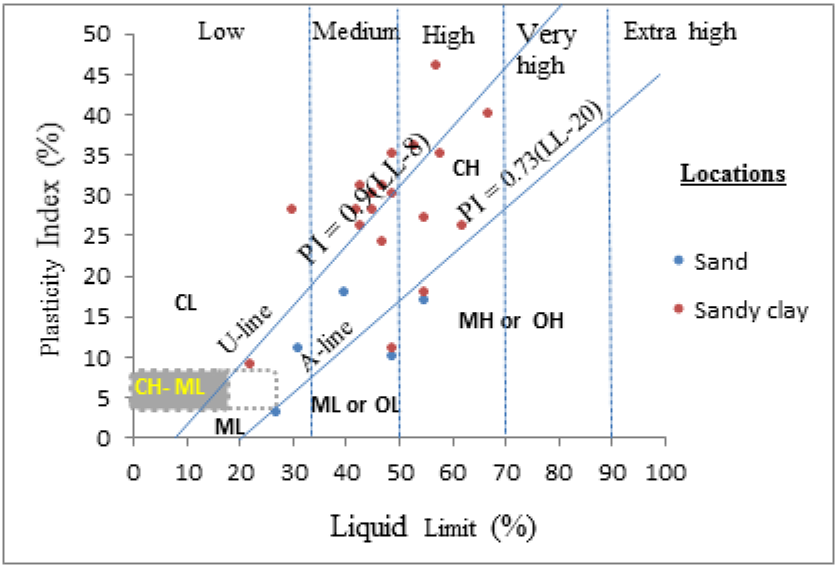


Fig. 4: Plasticity Chart of all the soil sample.

The overlying layers exhibited lower resistivity ranging within 3 and 240Ωm which can be attributed to increase in the water content according to (Telford, 1977).

4.3 Correlation between electrical resistivity and geotechnical properties

The result obtained from electrical resistivity and geotechnical properties were subjected to statistical analysis to determine the relationship between electrical resistivity and various properties of soil. The least squareregression method of different curve fitting approximations namely; logarithmic, exponential, polynomial, and power were applied and the best approximation equation with the highest determination coefficient of (R^2) was adopted.

The relationship between electrical resistivity and some of geotechnical properties of soil such as moisture content, angle of internal friction, cohesion, plasticity index and liquid limit were ascertained. Electrical resistivity and NMC of soil values demonstrated an inverse relationship through the power function. The power correlation indicated a good regression coefficient for all soil samples with determinationcoefficient (R^2) = 0.5 as illustrated in Fig. 5. The correlation of electrical resistivity and NMC was determined for different lithology. In silty sand samples, the determination coefficient of R^2 = 0.7 was recorded while a moderate determination coefficient of R^2 = 0.4 was observed in sandy clay. Several authors have reported that electrical resistivity value reduces with increase in gravimetric moisture content of soils. This is as a result of movement of ionic molecule within the pore space of saturated soil that enhances conductivity and on other hand reduces resistivity (Islam, et al 2020; Pozdnyakova, 1999; Siddiqui et al 2012;Cosenza et al 2006; Schwartz et al 2008; Ozcep et al 2010). The resistivity - moisture content relationship in this current research is in line with other published works (Siddiqui et al 2012;Cosenza et al 2006; Syed et al 2014; Ozcep et al 2010).

Electrical resistivity was observed to have a positive correlation with the angle of internal friction.It is displayed by the polynomial function of the silty sand samples with determination coefficient of R^2 = 0.5 (Fig. 6). It has been reported in several literatures that electrical resistivity increases with an increasing angle of internal friction (Islam et al 2020; Siddiqui et al 2012; Siddiqui et al 2013; Osman et al 2014). Shear strength parameters of a soil is dependent on the nature of particle structure and arrangement (Islam et al 2020). The internal friction angle depends on the amount of clay content in a lithology,which invariably determine the interconnectivity of the soil porosity and aid the motion of the ionic molecules that affects resistivity.

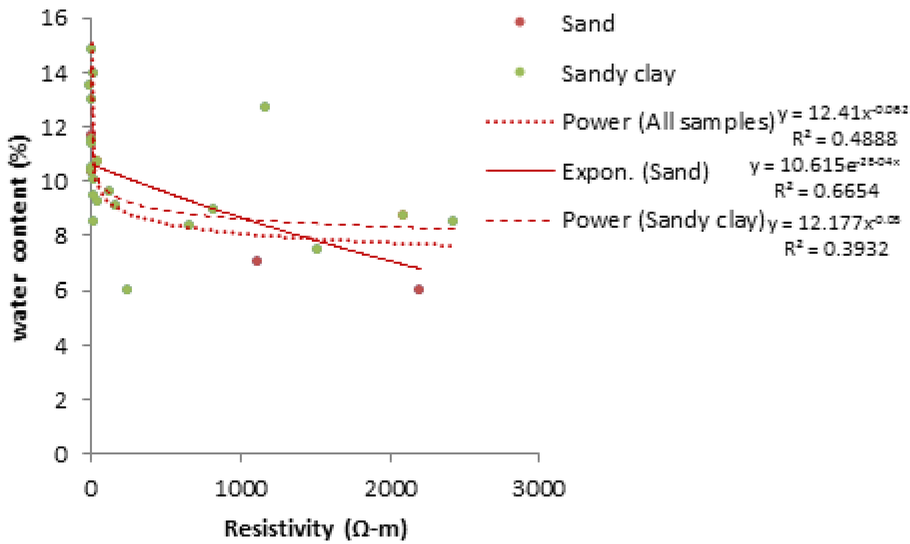


Fig. 5: Correlations of soil water content and electrical resistivity.

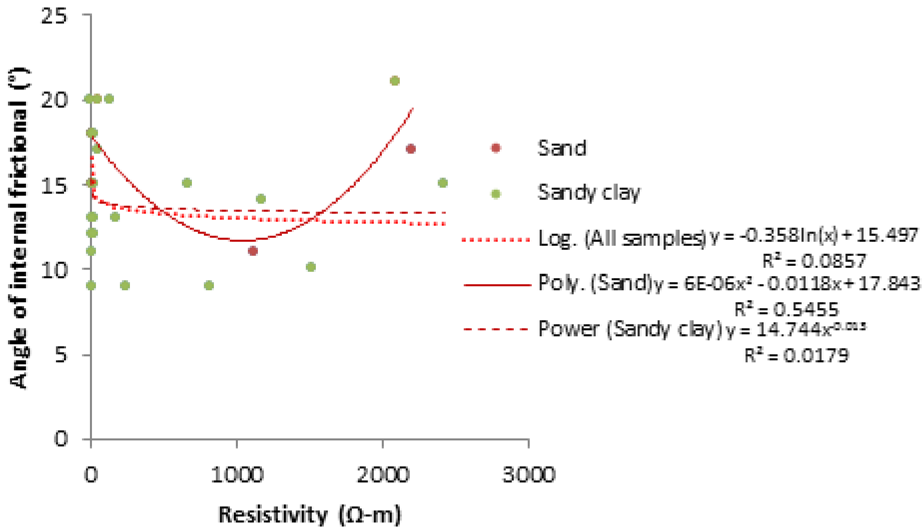


Fig. 6: Correlations of soil internal frictional angle and electrical resistivity.

The angle of internal friction has a nonlinear relationship with the degree of saturation (Islam et al 2020; Sadek,1993; Yan et al 2017). This premise is supported by low moisture contents with a higher angle of internal friction as observed in the silty sand samples within the study area. Likewise, a lower angle of internal friction was portrayed in the sandy clay which has high moisture content. Therefore, higher and lower resistivity is correlated to internal frictional angle that exist within the soil.Cohesion indicated a weak relationship with resistivity for the entire soil samples. Silty sand and sandy clay samples show that cohesion increases with decrease resistivity inversely (Fig .7). These findings are in agreement with other author which states that shear strength parameters decrease with increasing water content and on other hand decreasing electrical resistivity (Siddiqui et al 2012; Spoor et al 1979). An inverse relationship between cohesion and electrical resistivity has also been earlier reported by (Islam et al 2020; Siddiqui et al 2012; Siddiqui et al 2013).

There is a moderate correlation between electrical resistivity and plasticity index in all sample with a determination coefficient of R^2 = 0.4. Similarly, determination coefficients for silty sands and sandy clay were found to be R^2 = 0.2 as shown in Fig. 8. Siddiqui et al. (2012) and Abu-Hassanein et al. (1998) also reported a similar relationship between plasticity index and electrical resistivity of soil. Liquid limit showed a similarly moderate correlation with resistivity (R^2 = 0.3) as seen in Fig. 9. It had been established that soils with higher plasticity index, high percentage of clay, or a smaller coarse fraction normally have lower electrical resistivity (Abu-Hassanein et al 1996), and this theory is in line with the result of this research.

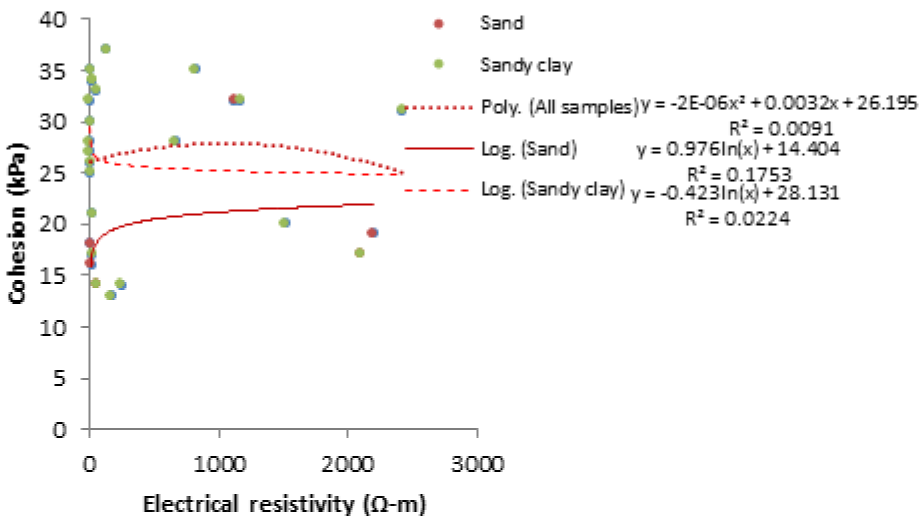


Fig. 7: Correlations of soil cohesion and electrical resistivity.

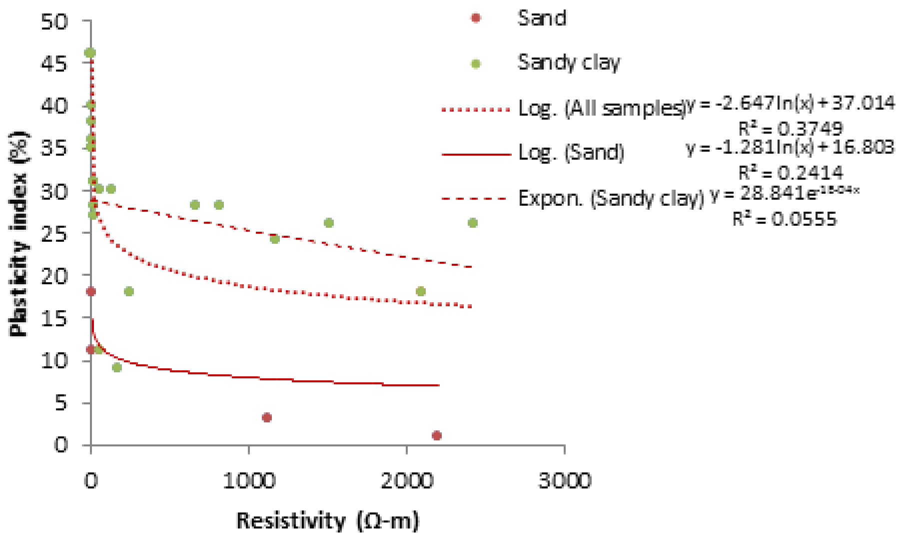


Fig. 8: Correlations of plasticity index and electrical resistivity of soil.

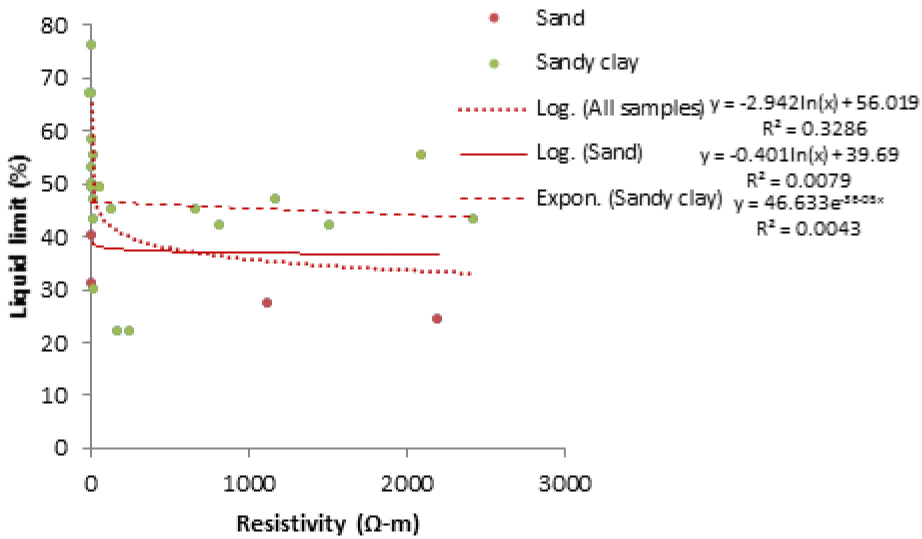


Fig. 9: Correlations of soil liquid limit and electrical resistivity.

Table 2 summarizes the results from correlation analysis, and it can be concluded that both Schlumberger and Werner resistivity configuration methods could be a good tool for estimation of plasticity index and gravimetric moisture content for all samples, sandy and clay soils alike. Cohesion and angle of internal friction could be predictable with moderate accuracy. These premises are supported by previous research works (Islam et

Soil properties	Sample description	Equation	Coefficient (R^2)
cohesion (Kpa)	All samples	$-2E\text{-}06x^2 + 0.0032x + 26.195$	0.0091
	sandy sample	$0.976\ln(x) + 14.404$	0.1753
	Sandy-clay	$-0.423\ln(x) + 28.131$	0.0224
Angle of internal Friction	All samples	$-0.358\ln(x) + 15.497$	0.0857
	sandy sample	$6E\text{-}06x^2 - 0.0118x + 17.843$	0.5455
	Sandy-clay	$14.744x^{-0.013}$	0.0179
Water content (%)	All samples	12.41x-0.062	0.4888
	sandy sample	$10.615e^{-2E\text{-}04x}$	0.6654
	Sandy-clay	$12.177x^{-0.05}$	0.3932

al, 2020; Pozdnyakova, 1999; Siddiqui et al 2012).

Liquid Limit (%)	All samples	-2.942ln(x) + 56.019	0.3286
	sandy sample	-0.401ln(x) + 39.69	0.0079
	Sandy-clay	$46.633e^{-3E-05x}$	0.0043
Plasticity (%)	All samples	-2.647ln(x) + 37.014	0.3749
	sandy sample	-1.281ln(x) + 16.803	0.2414

Table 2: Results of regression analysis between *resistivity* and *geotechnical parameters*

5.0 Conclusion

The relationship between electrical resistivity and the geotechnical properties of soils of Eha- Amufu and its environs was studied to determine the possibility of measuring electrical resistivity for quick estimation and characterization of geotechnical parameters of in-situ soils. Electrical resistivity methods are non-destructive, cost effective compared to the traditional method of laboratory procedures. The results obtained from the correlation of resistivity with the various soil properties showed a greater possibility of using in-situ electrical resistivity to forecast the geotechnical properties such as gravimetric water content, angle of internal friction, plasticity index, and cohesion.Therefore, electrical resistivity which is non-destructive cost effective can serve as alternative for quick estimation of geotechnical properties rather than the convectional way of obtaining soil properties.

Acknowledgements
The authors wish to appreciate the staff of the National Steel Raw Materials Exploration Agency, Kaduna, Nigeria for their laboratory assistance.

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