



doi:10.5281/zenodo.18767404

# Investigation of the Subsurface for Sustainable Infrastructural Development in Parts of Anambra State, Southeastern Nigeria, Using Electrical Resistivity Tomography (ERT)

<sup>1</sup>Obiadazie, S. C., <sup>2</sup>Nwozor, K. K., <sup>3</sup>Onyebueke, E.O., <sup>2</sup>Onyenweife, G. I. and <sup>2</sup>Mgbolu, C.C

<sup>1</sup>Department of Physics, Nwafor Orizu College of Education Nsugbe, Anambra State, Nigeria  
[chizobaumeh16@gmail.com](mailto:chizobaumeh16@gmail.com)

<sup>2</sup>Department of Geology, Chukwuemeka Odumegwu Ojukwu University Uli, Anambra State, Nigeria

<sup>3</sup>Department of Industrial Physics, Chukwuemeka Odumegwu Ojukwu University Uli, Anambra State, Nigeria

## ABSTRACT

Geophysical investigation was conducted within the sedimentary environments of Amansea, Mbaukwu, Igbariam, Oba, Okija and Umunze, all situated within the Anambra Basin. The study adopted the integration of Vertical Electrical Sounding (VES) and 2D Electrical Resistivity Tomography (ERT) techniques in delineating the depth to competent rock for sustainable foundation development of engineering infrastructure. Seven (7) VES and six (6) horizontal profiling (2D ERT) were carried out using Schlumberger and Wenner- $\alpha$  arrays, respectively. Omega 48 resistivity meter was used for data acquisition. Sounding curves were generated from the plots of resistivity-electrode spacing. The VES plots were subjected to partial curve matching using interpex sounding inversion software to generate the geoelectric sections of the study areas. The geoelectrical sections revealed resistivity variations with respect to thickness and depth of the different lithology. Data from ERT was processed using RES2DINV software to generate 2D inverse model resistivity sections of the studied areas. Information obtained from these electrical resistivity techniques correlated effectively with the information from borehole log drilled around the study. The interpretation of both data/sections suggested that the studied areas are underlain by: top soil with resistivity range of (8.6537 - 3764.10  $\Omega$ m); weathered and partially weathered layers with resistivity range of (4.0663 - 302.69  $\Omega$ m), interpreted to be shale and shaley sand formations; and finally, the competent layers with resistivity range of (305.02 - 2029.20  $\Omega$ m) suggested to be sand formation.

**Keywords:** Geoelectrical Section, Subsurface Modelling, Infrastructure, Competent Rocks, Electrical Resistivity Tomography, Sounding profiling.

## 1.0 INTRODUCTION

Nigeria is faced with increasing rate of structural failures, collapses and the significant loss of life and properties which emphasized the need for effective geophysical investigation of subsurface for engineering constructions (Ede, 2010; Adebo, 2021). Globally, structural failures/collapses are considered to be caused by one of the two major factors: natural or man-made factors. The natural factors include but

not limited to landslide, earthquake, flood & erosion, mud-flow, thunder storm and hurricane while man-made factors are reported to be as a result of human errors within the entire process of planning, designing, construction and maintenance of structures (Dimuna, 2010; Amadi et al., 2012; Mansur and Kouider, 2017). The rate of the collapse and the magnitude of destruction were observed to be low in developed nations where strict adherence to building codes and ethics of professionalism are obtainable (Ede, 2011; Mansur and Kouider, 2017). In these developed countries, natural factors usually, are observed to be the predominant cause of structural failure, consequently, they are considered during planning and design to accommodate possible occurrences, especially for locations prone to such natural disasters (Ellingwood & Dusenbury, 2005). Contrarily, developing nations like Nigeria, have suffered frequent collapse of buildings predominantly resulting from man-made factors (Ayininuola and Olalusi, 2004; Dimuna, 2010; Amadi et al., 2012). However, there are very rare cases where collapse is caused by natural factors considering the country's geographical location, except few cases of erosion and flood (Adama and Kouider, 2017). Structural failures in Nigeria have mostly been attributed to man-made factors including but not limited to poor building materials, poor engineering design, inadequate supervision, quake engineers, poor funding, the geologic properties of the host subsurface notwithstanding (Adebo et al., 2021).

The earth is comprised of subsurface lithologies that have different physical variations and properties. Few meters below the earth's surface are subject to human activities (engineering structural/building foundations, groundwater/borehole drilling, mining activities, oil and gas exploration), and potential geohazards (landslides, shallow active faults, land subsidence, earthquakes, voids) (Petrit et al., 2018). The sources of hazards in civil engineering discipline, has been observed to result essentially from undetected near-surface structures, such as cavities and/or inhomogeneities in the subsurface structures and materials (Soupios et al., 2007). The failure/collapse in buildings, bridges, or any form of erected structures on the earth have been linked to lack or inadequate pre-construction subsurface investigation (Ilugbo et al., 2018b; Ben-Owope, 2019; Bawallah et al., 2019b; Bawallah et al., 2020). Foundation failure has been associated with differential settlement of subsurface soil and presence of geologic fissures such as faults, fractures, and shear zones beneath the construction site (Oyedele et al., 2020).

The geologic properties of the host subsurface play a significant role in the integrity/stability of the construction/building (Aigbedion et al., 2019). Geophysics is the application of physical parameters to determine subsurface geological properties (Adebo, 2021). Geophysics can be applied for exploration purposes to provide useful information regarding the early detection of potentially dangerous subsurface conditions (Soupios et al., 2007). Geophysical investigation in geophysics, precisely, the electrical resistivity survey has become a promising approach in the investigation of the subsurface geo-materials for proper evaluation of foundational materials' strength (Aning et al., 2019). Advances in technology have brought about innovations and development of geophysical methods to solve various problems encountered by mankind in his quest for better life and electrical resistivity method is not left out in this move (Ayolabi et al., 2012a). The electrical resistivity survey is a unique geophysical tool used in exploration of natural resources, environmental issues and geotechnical investigations, and is probably the most common method applied to shallow subsurface investigations in imaging the subsurface structures for early detection of potentially dangerous subsurface condition such as Cracks, voids, cavities and in subsurface investigations for precise construction and determination of the nature of subsurface strata without excavation (Dahlin and Zhou, 2002; Ayuk, 2005; Burger et al., 2006; Lech et al., 2020; Adebo et al., 2021; Sonawane et al., 2023).

Ademila, 2022 combined very low frequency electromagnetic (VLF-EM) and electrical resistivity methods to provide detailed information on subsoil profile for documentation and references for durable and sustainable construction work. Thirteen traverses were established from which geophysical data were acquired. The acquired data were processed, inverted and interpreted. VLF-EM 2D inverted models revealed conductive zones at some locations suggesting incompetent zones, responsible for structural instability. Ogungbe et al., (2012) applied 2D resistivity imaging and vertical electrical sounding (VES) surveys in the study of the level of groundwater contamination at Ile-Epo dumpsite in Agbado Oke-Odo Local Council

Development Area (LCDA), Lagos State, Southwestern, Nigeria. A total of nine vertical electrical soundings and four 2D electrical imaging adopting Wenner arrays. The result of data interpretation revealed that the study area is characterized by sand and clay formations. Onyenweife et al., 2024, employed electrical resistivity vertical sounding to investigate the subsurface to ensure development of sustainable infrastructure across the study area. Apparent resistivity data were plotted against the electrode spacing to produce 2D profiles which showed layer structure across the study area. The layers include clayey, sandy, clayey sand, water saturated and faulted zones. The result of the investigation is important for sustainable designing and constructions. Onyenweife et al., 2025 carried out electrical resistivity logging on existing wells at Anaocha Local Government Area, Anambra State to evaluate the geological formation of the subsurface and well efficiency. The results showed the geological constituents of the study area. Onyebueke et al., (2018) integrated high-resolution shallow seismic with electrical resistivity method to demonstrate the potential and the advantages of combining several surface geophysical techniques for near-surface investigations, especially for hydrogeological prospecting and site characterization in South Africa. Ademilla (2022) carried out pre-foundation geophysical investigation of a site for structural development in Oka, Nigeria employing the electrical resistivity survey. Adebo et al., (2021) applied electrical resistivity method to site characterization for construction purposes at Institute of Agriculture Research and Training Moor Plantation Ibadan, Southwestern Nigeria, to ascertain the suitability of the proposed site for building construction and usage. The results were qualitatively and quantitatively interpreted and are presented as sounding curves and geoelectric sections. The 2-D imaging gave information on the subsurface characteristic in the area with generally low apparent resistivity indicating low competence material. Geophysical data interpretation can image the subsurface to the depths of competent layer and evaluate the real distribution of geological earth material (Ayolabi et al., 2012b), hence the use of electrical resistivity to delineate the depth to competent rocks for sustainable infrastructural development in Anambra State.

## 2.0 GEOLOGICAL SETTING/SITE LOCATION

Geographically, the study areas lie within longitude  $6^{\circ} 46' 0''$  E to  $7^{\circ} 14' 0''$  E and latitude  $50^{\circ} 54' 0''$  N to  $6^{\circ} 20' 0''$  N in Anambra state Southeast Nigeria, with diverse features ranging from towns, expressways, main road, secondary roads, rivers and lake (Figure 1). The test locations and geo-reference points of the areas under study are presented in Table 1. The study areas are underlain by Imo-shale, Ogwashi-Asaba and Ebenebe sandstone formations all within Anambra Basin. Anambra basin is a sedimentary basin in Southeast of Nigeria known for its Cretaceous to Paleogene age (Ben-Owope, 2019; Onyenweife et al., 2024), having about 6000 m of sedimentary rocks with various geological formations: Nkpolo Shale, Mamu Formation, Ajali Sandstone, Nsukka Formation, Ameki Formation and Ebenebe Sandstone. Nkpolo shale, Mamu formation, Ajali sandstone and Nsukka formation are the main formations.

### Imo Shale

The Amansea (VES 1 & 2), Mbaukwu (VES 3) and Igbariam (VES 4) data points are underlain by the Imo shale formation of the Anambra Basin (Figure 1). The Imo Shale a geologic unit in Nigeria, within the Anambra basin specifically, is Paleocene to Eocene, specifically, Paleocene to Lower Eocene in age and the oldest formation in the Anambra Basin, approximately, 50 - 60 million years ago. It is predominantly composed of thick sequences of blue and dark fine textured/fine grained, fissile (layered and easily split along planes of weakness) grey shales with occasional bands of clay-stones (mixtures of clay, ironstone and sandstone bands with limestone intercalations). Imo shale has been identified as a potential source rock for hydrocarbon generation, particularly gas. It is also known for its marine fossils, suggesting deposition in a marine environment. Laterally, Imo shale correlates with the Akata Formation in the Niger Delta basin, it's a surface equivalent to the subsurface Akata Formation in the Nger-Delta Basin. Lithology: Shales, claystones, calcareous mudstones, siltstones, ironstones, and lenses of sandstones. May contain minor occurrences of clayey ironstone and thin sandstone bands. Soil formation within the Imo shale have moderate/average to high Atterberg limits, low shear strength, may pose foundation problems for buildings. Mbaukwu, Igbariam, Amansea, are overlain by Imo Shale. Depositional environment: Shallow marine shelf, with possible near-shore or shoreface environments.

### Ogwashi-Asaba Formation

The Oba (VES 4) and Okija (VES 5) study areas are underlain by the Ogwashi-Asaba Formation part of the Anambra Basin (Figure 1). Ogwashi-Asaba Formation is a geological formation in southern Nigeria, specifically within the Anambra and Niger-Delta basin. The Ogwashi-Asaba Formation conformably overlies the Ameki Group. Laterally, it is a surface equivalent to the subsurface Agbada Formation in the Niger-Delta basin. It is Eocene to Oligocene (Oligocene-Miocene) in age. The lithology consists primarily of an inter bedding of coarse-grained sandstone, lignite seams (coal deposits), and light-colored clays of continental origin representing a shift from marine to continental depositional environments. Continental origin with tidally influenced sedimentation. Ogwashi-Asaba Formation is known for its lignite-rich beds, which have been studied for their geochemical composition. The presence of lignite seams suggests swampy conditions existing during its formation. Heavy mineral analysis suggests the sandstones have a specific provenance and tectonic setting. Oba, Okija axis of the studied area, is underlain by the Ogwashi-Asaba Formation.

### Ebenebe Sandstone

Umunze area of study is underlain by the Ebenebe sandstone part of the Anambra Basin. The geoelectric section VES 6 is composed of six geoelectric layers (Figure 1). Ebenebe Sandstone is a geological formation within the Anambra Basin, southeast of Nigeria. Primarily, the Formation comprises of sandstone (coarse-grained), featuring cross-bedding structures depicting aquifereous zone which can be sources of groundwater. Its depositional environment is fluvial or of shallow marine origin. Umunze axis belongs to this formation.

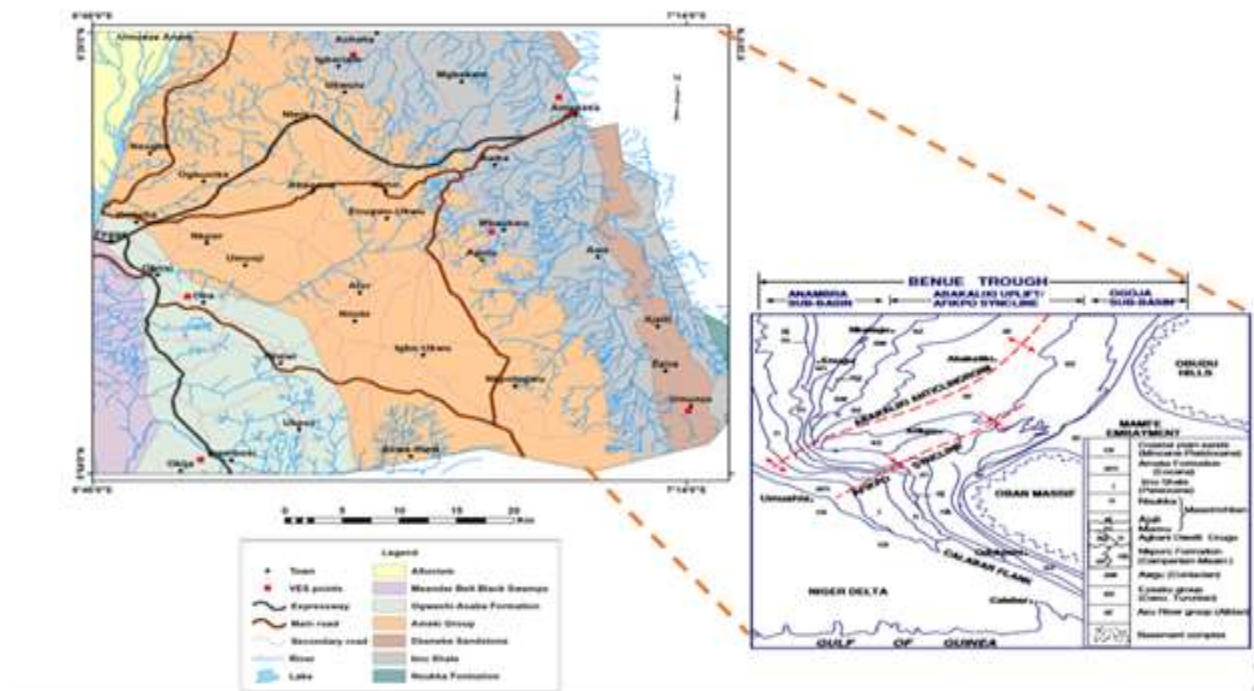


Figure 1: Geology Map of Anambra Basin showing the Study Areas.

### 3.0 METHODOLOGY

#### 3.1 Materials and Method

Electrical resistivity method involving the integration of the techniques of Wenner- $\alpha$  horizontal profiling for 2D Electrical Resistivity Tomography (ERT) (Figure 2a) and Schlumberger depth sounding for Vertical Electrical Sounding (VES) (Figure 2b) using four electrodes (two current electrodes and two potential electrodes) was adopted in this study. The locations of the areas studied (the data points) in terms of the longitude, latitude and sea level elevation were obtained with Global Positioning System (GPS) at all the data acquisition points. Measurements were made by injecting known amount of electric current ( $I$ ) into the subsurface using the two current electrodes, and the measurement of the resulting potential difference ( $V$ ) between two points at the surface using the two potential electrodes. From the current ( $I$ ) and voltage ( $V$ ) values the resistive response ( the resistance  $R$ ) of the subsurface materials were obtained. A total of six (6) VES and horizontal profiling stations were carried out in the study. Omega 48 resistivity meter (Figure 2c) was used for data acquisition.

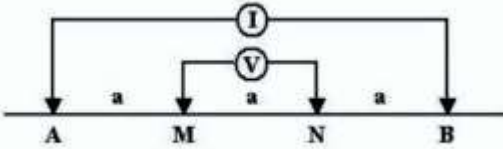


Figure 2a: Wenner- $\alpha$  Electrode Configuration/Array.



Figure 2c: Omega 48 resistivity meter.

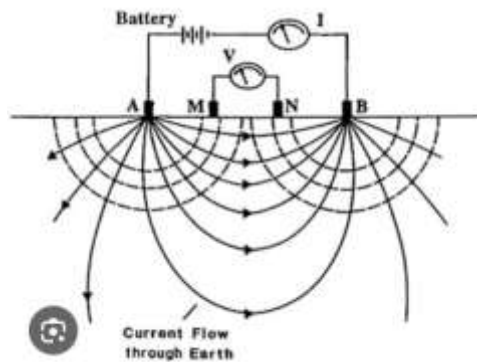


Figure 2b: Schlumberger Electrode Configuration/Array.

### 3.2 2D Electrical Resistivity Tomography (2D ERT) Data Acquisition and Processing.

The 2D Electrical Resistivity Tomography (2D ERT) measurements were carried out with equal electrode spacing of " $\alpha$ " = 3 m for successive measurements covering a lateral (horizontal) distance (AB m) of 100 m (Figure 3a). The measured resistance values were converted into apparent resistivity ( $\rho_a$ ) by multiplying the resistance ( $R$ ) with the geometric factor ( $K$ ) of the electrode array employed in the survey.

$$\rho_a = KR \dots \dots \dots \text{eqn (1)}$$

$$\rho_a = 2\pi\alpha R \dots \dots \dots \text{eqn (2)}$$

where  $\alpha$  = electrode spacing,  $R$  = the value of measured/field resistance and  $2\pi\alpha = K =$  the geometric factor for the Wenner- $\alpha$ electrode array.

Inverse modelling of the measured apparent resistivity data was carried out using RES2DINV software. The software automatically created the 2D model of the earth by dividing the subsurface into rectangular blocks. Thereafter, it calculated the apparent resistivity values of the model blocks and compared them with the measured apparent resistivity values. The resistivity values of the model blocks were adjusted iteratively until the calculated apparent resistivity values of the model are in close agreement with the measured values. The result of this iteration process is the 2D inverse model resistivity section. This approach was employed for the generation of 2D inverse model resistivity sections at the data points (Figure 3a - f).

Figure 3a ERT at VES 1

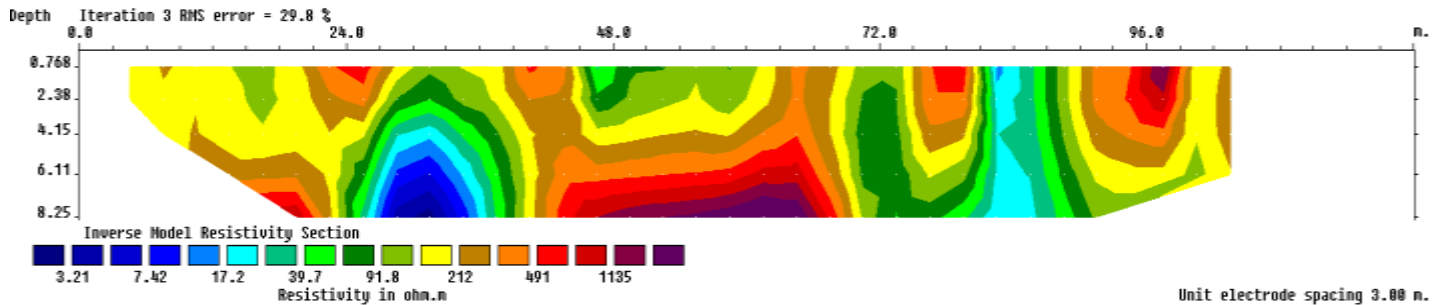


Figure 3b ERT at VES 2

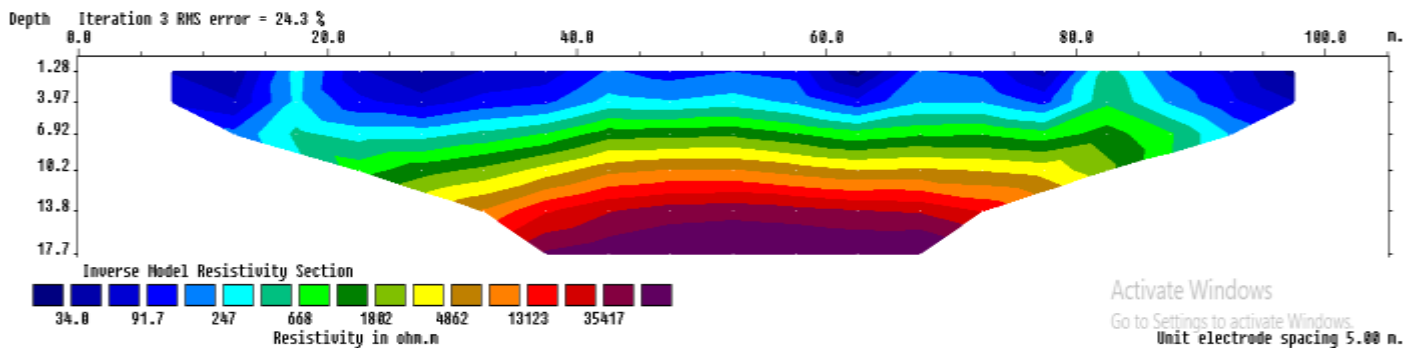


Figure 3c ERT at VES 3

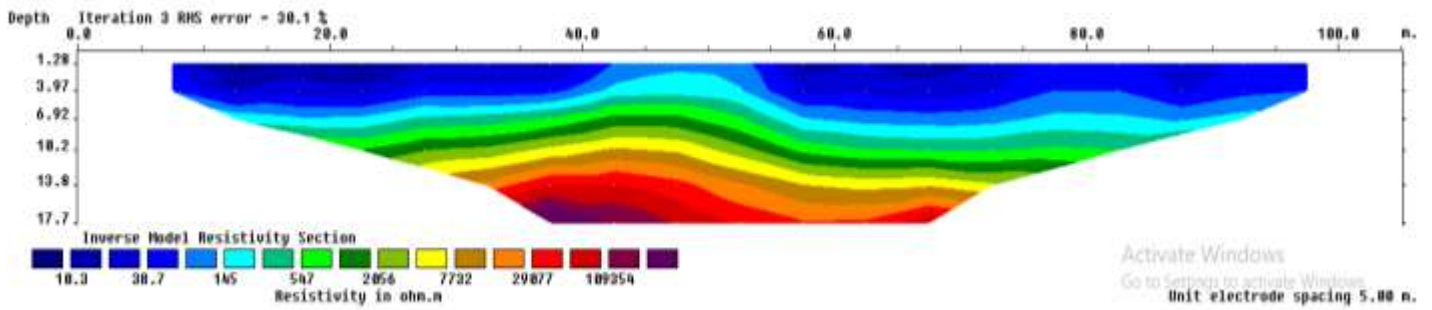


Figure 3d ERT at VES 4

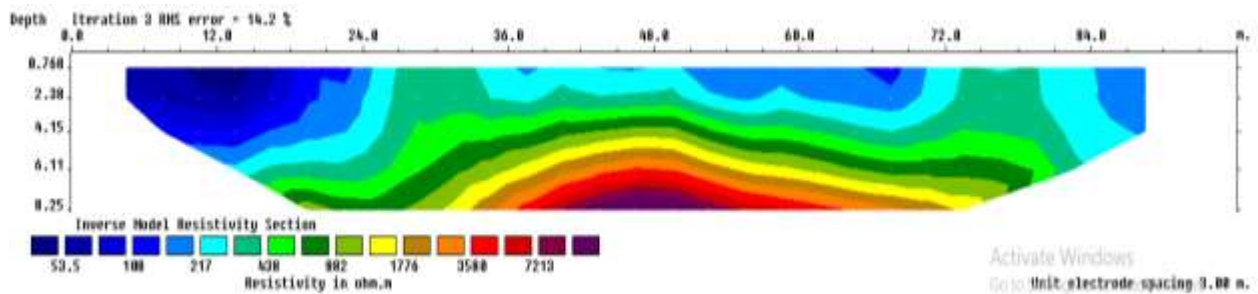


Figure 3e ERT at VES 5

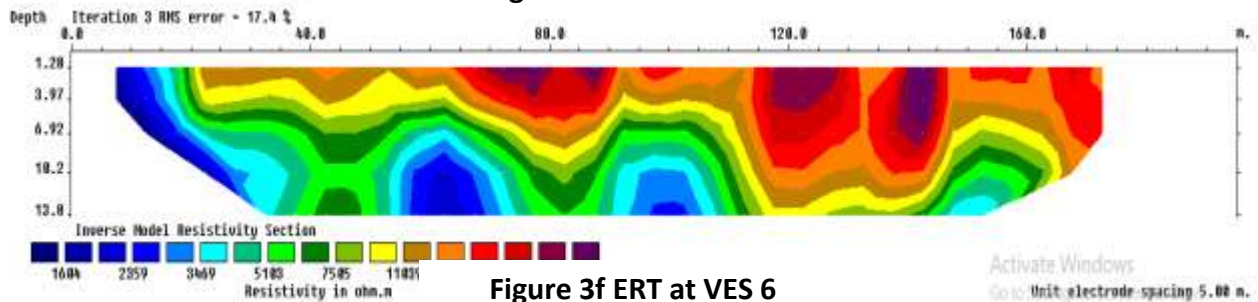


Figure 3f ERT at VES 6

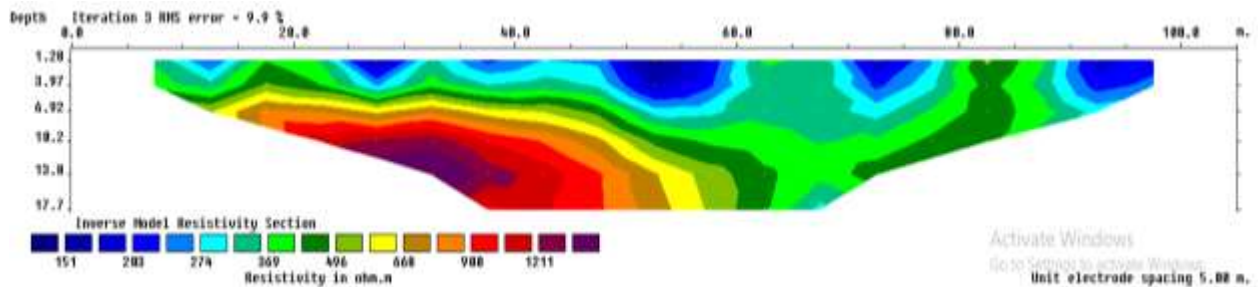


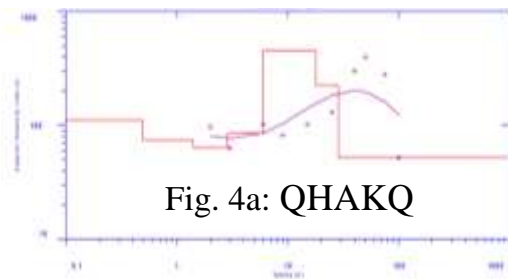
Figure 3: Electrical Resistivity Tomography (VES) Apparent Resistivity Data Acquisition and Processing.

For the VES measurements, a maximum current electrode separation (AB m) of 200 m and potential electrode separation (MN m) of 10 m were adopted in the survey using the Schlumberger electrode array (Figure 3b) principles. The measured/field resistance ( $R$ ) values were converted into the apparent resistivity ( $\rho_a$ ) values by multiplying the resistance ( $R$ ) with Schlumberger electrode configuration geometric factor( $K$ ) such that

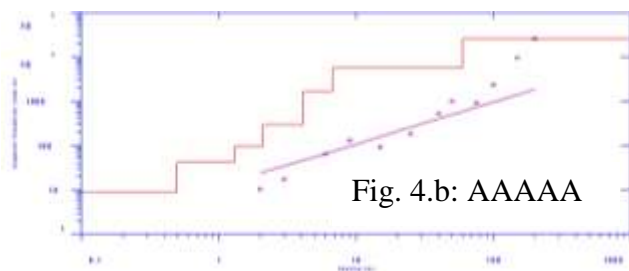
$$\rho_a = \frac{\pi \left[ \left( \frac{AB}{2} \right)^2 - \left( \frac{MN}{2} \right)^2 \right]}{MN} R = KR$$

where  $\frac{AB}{2}$  is the half current electrode spacing, MN is the potential electrode spacing while  $\frac{MN}{2}$  is the half potential electrode spacing,  $\pi$  is a constant,  $R = \frac{\Delta V}{I}$ .

The apparent resistivity values for each area were plotted against half current electrode separation (AB/2 m) on bi-logarithmic graph sheet using transparent tracing paper superimposed on the log-log paper. The sounding curves obtained were subjected to partial curve matching (Koefoed, 1979) using master curves and auxiliary curves (auxiliary point charts) (Orellana and Mooney, 1972) and were inspected to determine the number and nature of the layers. The results of the curve matching process (layer resistivity and their respective thickness) were fed into the computer as a starting model (input data) in an iterative forward modeling technique using Interpex sounding inversion computer software to vindicate the correlation of the field curve and the theoretical curve. The field data were compared with the data derived from a layer model obtained by curve matching. The parameters of the layer model were adjusted iteratively so as to bring close the agreement between the two data sets (model data and field data). Figure 4a-b represent parts of Vertical Electrical Sounding (VES) curves and Tables of the study area.



Resistivity Model					
Surface Elevation: 151.00				Fitting Units:	
<input type="checkbox"/> Use Depth Instead of Thickness					
#	Rho	Fix?	Thick	Depth	
1	111.79	<input type="checkbox"/>	0.49124	0.49124	
2	74.370	<input type="checkbox"/>	0.90797	1.3992	
3	63.621	<input type="checkbox"/>	1.4548	2.8540	
4	85.329	<input type="checkbox"/>	3.0712	5.9252	
5	452.76	<input type="checkbox"/>	11.930	17.855	
6	223.98	<input type="checkbox"/>	10.659	28.514	
7	51.920	<input type="checkbox"/>			
8		<input type="checkbox"/>			
9		<input type="checkbox"/>			



Resistivity Model					
Surface Elevation: 0.0000				Fitting Units:	
<input type="checkbox"/> Use Depth Instead of Thickness					
#	Rho	Fix?	Thick	Depth	
1	8.8784	<input type="checkbox"/>	0.49498	0.49498	
2	41.719	<input type="checkbox"/>	0.79493	1.2899	
3	94.988	<input type="checkbox"/>	0.79493	2.0848	
4	295.80	<input type="checkbox"/>	2.0322	4.1171	
5	1684.0	<input type="checkbox"/>	2.6090	6.7261	
6	5645.0	<input type="checkbox"/>	52.965	59.691	
7	25882.	<input type="checkbox"/>			
8		<input type="checkbox"/>			
9		<input type="checkbox"/>			

**Figure 4a - b: Vertical Electrical Sounding (VES) curve types and Tables generated in the study area.**

#### 4.0 RESULTS AND DISCUSSION

Seven (7) VES curve types; Amansea - VES 1& 2 (QHAKQ& AAAKQQ); Mbaukwu - VES 3 (AAAAA); Igbariam = VES 3 (HA); Oba = VES 4 (AAKQQ); Okija = VES 5 (AAKQHA) and Umunze = VES 6 (AAAK) (Figure 4a - b) were obtained in these areas revealing the different layers in terms of their respective apparent resistivity values, thickness and depth in the various areas studied. The geoelectric section of the study area is represented in figure 5a - c.

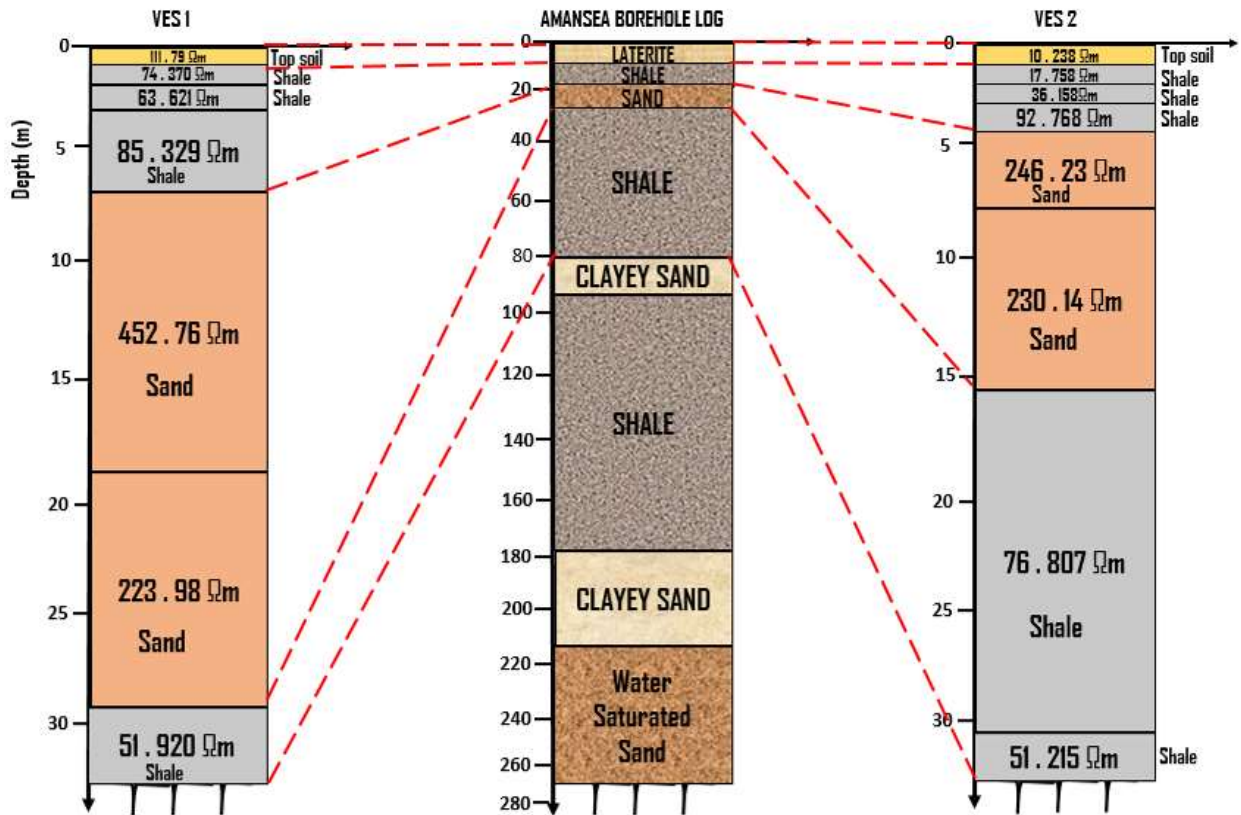
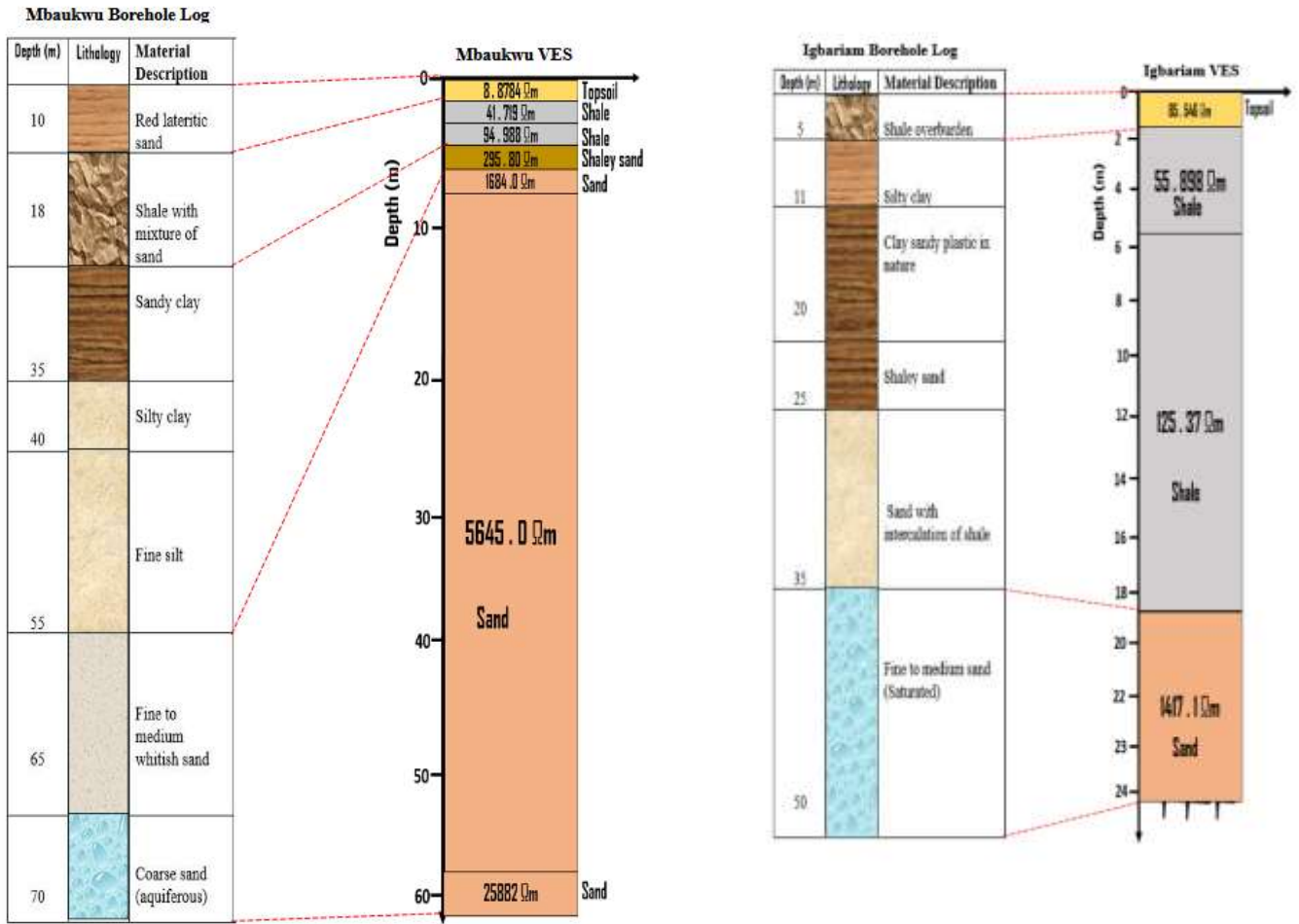
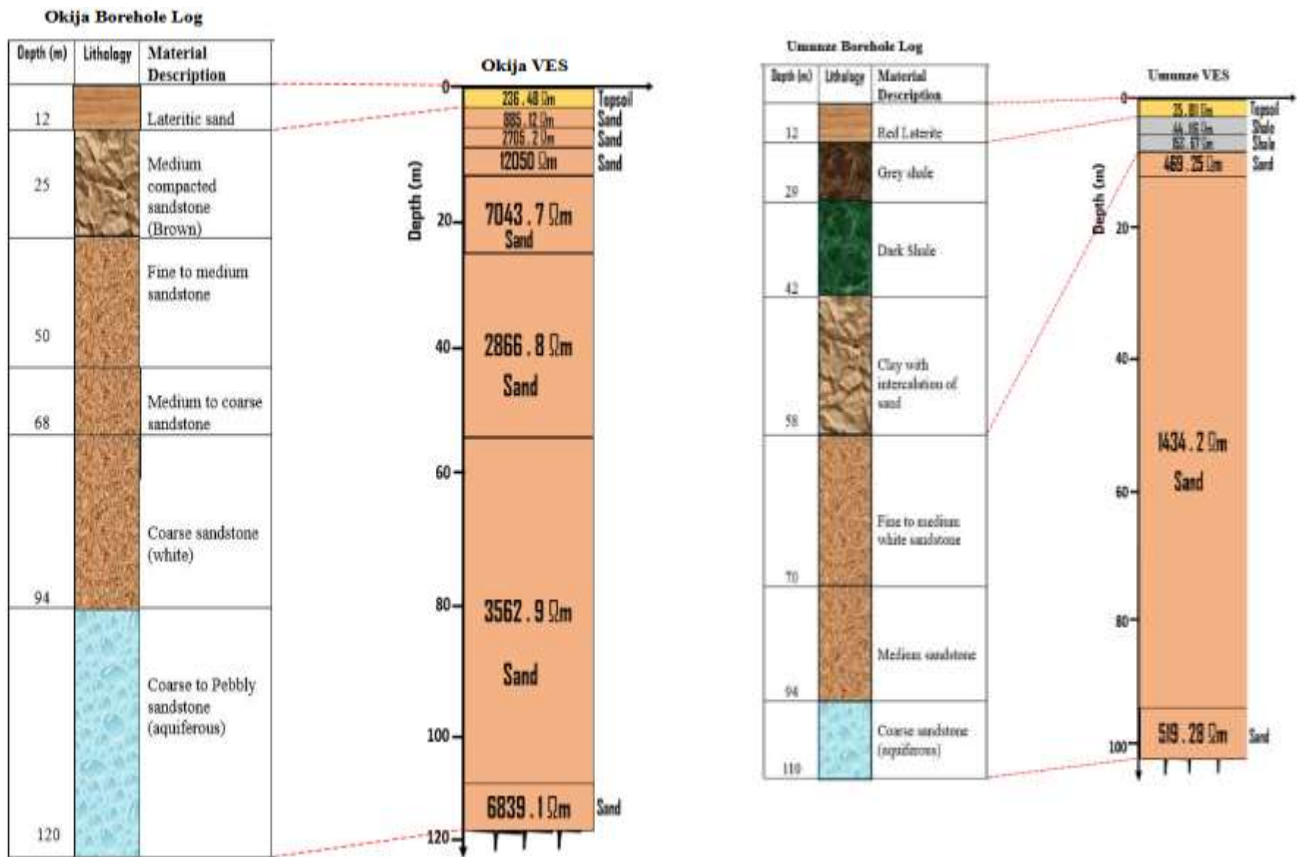


Figure 4a: The geoelectric section of VES 1 & 2 with the borehole log of the study the study area



**Figure 4b: The geoelectric section of VES Mbaukwu and Ighariam with the borehole log of the study the study area**



**Figure 4c: The goelectric section of VES Okija and Umunze with the borehole log of the study the study area**

**Table 1: Summary of VES Goelectric Sections Results**

VES No.	Depth to weathered zones (m)	Thickness of weathered zones (m)	App. Res. of weathered zones (Ωm)	Depth to competent zone (Ωm)	App. Res. competent zone (Ωm)
1	1	6	74.370 - 85.329	7	223.98 - 452.76
2	1	3	17.758 - 92.768	4	230.14 - 246.23
3	1.5	5	41.719 - 295.80	6	1684.0 - 5645.0
4	1.6	16	55.898 - 125.37	18.4	1417.1
5	2	2	37.509	4	521.08 - 1508.0
6	-	-	-	2	885.12 - 7043.7
7	2	4	44.116 - 153.67	6	469.25 - 1434.2

Quantitative interpretation of the sounding curves provides the goelectric parameters used in the generation of their respective goelectric sections (Table 1). Quantitative interpretation of the geologic sections was done in terms of subsurface lithology, revealing the pattern of resistivity variations with thickness and depth at each of the studied area. The goelectric sections therefore represent the geologic sequence of the study areas mapped with respect to resistivity, thickness and depth of current penetration.

**Electrical Resistivity Tomography (2D ERT) Interpretation**

The subsurface features on the 2D Inverse Model Resistivity Sections (ERT 1 - 6) are coincident with the features on their respective goelectric sections (Figure 3a - f). Different goelectric segments were encountered in the various profiles with each segment represented by a distinct colour. The 2D Inverse Model Resistivity Sections were interpreted with respect to subsurface lithology using the apparent

resistivity distribution, depending on lateral and vertical continuity and geometry of the image responses and interpretations were made in terms of subsurface lithology. The lithologic layers are distinguished at these study locations with maximum depth of current penetration of 17.7 m.

The resistivity value ranges of the geoelectric layers of the 2D ERT sections (ERT 1 - 8) and the corresponding geoelectric sections of the VES (VES 1 - 8) correlated effectively with each other and with the lithologic logs (borehole information) from boreholes drilled around each of the studied areas. Generally, the apparent resistivity values were classified into five classes namely: very low, low, moderate/relatively high, high and very high apparent resistivity. The very low to low resistivity range of 0.0 - 200  $\Omega\text{m}$  and 200 - 400  $\Omega\text{m}$  respectively are classified as the weathered layers composed of expansive clay/saturated clay/shale and sandy clay/shaley clay geological materials which are inimical to engineering foundation stability and integrity. The moderately/relatively high resistivity range of 400 - 600  $\Omega\text{m}$  are classified as the partially/moderately weathered layers composed of clayey sand/shaley sand formation considered as relatively/moderately competent zones for small/average/light/low-rise engineering infrastructures. The high to very high resistivity responses (fresh basement) with resistivity range of 600 - 850  $\Omega\text{m}$  and  $850 \geq 100000 \Omega\text{m}$  respectively considered to be sand/laterite/fresh basement formation are the recommended competent zones for the establishment of engineering infrastructural foundation of any size for sustainable development of infrastructures.

The first geoelectric layer (layer 1) of the geoelectric sections (VES 1 - 3) (Figure 4) are composed of the topsoil with resistivity range of 8.8784 - 236.48  $\Omega\text{m}$  and thickness of about 0.49124 - 1.6022 m beneath the surface. In the 2D inverse model resistivity sections (ERT 1 - 3) of these areas, the first geoelectric layer is composed of topsoil with resistivity range of 10.3 - 491  $\Omega\text{m}$  with thickness of about 2 - 3.97 m beneath the surface. Integrating the two sections (2D ERT & VES sections), the topsoil of both sections is composed of varying resistivity materials (8.8784 - 491  $\Omega\text{m}$ ) suggesting the presence of decomposed organic materials, plants and vegetable remains, presence of expansive/saturated clayey/shaley materials and other sand filling materials. The resistivity values of topsoil usually is not considered since it is often excavated, engineering infrastructural foundations are not found or established on the topsoil.

Layers 2 - 7 of VES 1; layers 2- 8 of VES 2; layers 2 - 4 of VES 3; layers 2 -3 of VES 4 with resistivity range of 17.758 - 452.76 $\Omega\text{m}$  at a depth of 1 - 19.0 m beneath the surface are the weathered layers of their respective geoelectric sections. Integrating this with the features on the corresponding 2D inverse resistivity model sections, revealed that the second layer with resistivity range of 17.2 - 491  $\Omega\text{m}$  to a depth of about 6.11 m composed of saturated clay/shale/clayey sand/sandy clay/shaley sand materials. The second layer is considered to represent the weathered layer and partially weathered layers of the areas of study. These weathering layers with very low and low resistivity responses indicates water saturation zones, fractures, faults, basement depressions that could be a threat to the stability and integrity of engineering constructions in these areas of study. The two units (weathered and partially weathered) also constitute the hydrogeologic units recommended for groundwater exploration in the study areas.

The third geoelectric layer (layer 3) at a depth of about 6.11 - 17.7 m (depth of current termination/penetration) for ERT 2 & 3 show resistivity range of 547 - 109354  $\Omega\text{m}$  beneath the surface whereas the corresponding layers in ERT 1 reveal resistivity range of 17.2 - 1135  $\Omega\text{m}$ . The high resistive portions on the 2D ERT 2 & 3 are coincident with the competent layers on their respective geoelectric sections with resistivity range of 1417 - 25882  $\Omega\text{m}$  at a depth of 4 - 60 m. The high to very high (fresh basement layers) are suitable for sustainable development of engineering infrastructures. The resistivity range of ERT 1 across the two sections reveals the presence of pockets of very low to low resistive geomaterials (weak geologic materials) in different directions across the traverse indicative of water saturated zones. Resistivity of these layers across the two sections (VES 1 and ERT 1) indicate water bearing fractured basement zones which could form hydrogeologic units of the area for groundwater development but incompetent zone for massive engineering construction purposes.

The first geoelectric layer (layer 1) of VES 4 & 5 geoelectric sections is composed of the topsoil with resistivity range of 18.332 - 236.48 $\Omega\text{m}$  and thickness of about 0.56838 - 0.74151 m beneath the surface. The 2D inverse model resistivity sections (ERT 4 & 5) along the VES 4 & 5 data points, show the first

geolectric layer (topsoil) with resistivity range of 53.5 - 23888 $\Omega$ m with thickness of about 2.38 - 3.97 m beneath the surface. Integrating the two sections (VES & ERT) from the study areas show the topsoil is composed of different geologic materials with varying resistivity values (very low to very high) some of which are saturated clay/shale/ sand/laterite materials. The apparent resistivity of the topsoil is not considered as it is usually excavated in case of engineering infrastructure foundation purposes.

Layer 2, 5 - 6 of VES 4 with resistivity of 37.509  $\Omega$ m, 389.16 - 130.92  $\Omega$ m respectively reflect/indicate the presence of saturated/expansive clay/shale and other weak very low resistive geomaterials at a depth of 0.56838 - 2.7425 m, 40 to the depth of current penetration respectively.

The second layer (layer 2) of VES 5 to the depth of current penetration (0.74151 - 112.70 m) showed very high resistivity response (fresh basement bedrocks).

Layer 3 - 5 of VES 5 show resistivity range of 521.08 - 5508.9  $\Omega$ m at a depth of about 2.7425 - 39.995 m. Integrating the information from the VES 4 & 5 geolectric sections with the features on their respective 2D inverse resistivity model sections (ERT 4 & 5), the second layer (layer 2) of ERT 4 at a depth of about 2.38 - 6.11 m is composed weak and relatively weak geologic materials with resistivity range of 108 - 7213 $\Omega$ m affirming the second layer of the study area to be the weathered and hydrogeologic zone of the study area (Oba) incompetent/unsuitable for sustainable development of engineering infrastructures. Also, the resistivity values observed at VES 5 geolectric section coincides with the features on its 2D ERT which revealed very high resistivity responses (1604 - 23888  $\Omega$ m) referred to as fresh basement bedrock suitable for any form of engineering infrastructural foundation across /along the 2D the study area (Okija).

Integrating the information from the VES 6 geolectric section with the features on the 2D ERT section, the two sections correlated effectively with the topsoil of the two geolectric sections showing the resistivity range of 25.811 - 496  $\Omega$ m indicating the presence of very weak to relatively weak/high (very low to relatively high) resistivity materials on the surface of the study area suggested to be decomposed organic materials, plants and vegetable remains, and other very weak geologic sand filling materials such as expansive/saturated clayey/shaley formations. The topsoil is excavated in case of engineering infrastructure foundation purposes; hence the apparent resistivity value is not considered.

Second to fourth geolectric layer (layer 2 - 4) and the sixth layer (layer 6) with resistivity range of 44.116 - 519.28 $\Omega$ m at a depth of 3 - 9 m and 95 - 105 respectively beneath the surface are the very low to moderately/relatively high resistivity responses observed along the VES 6 geolectric section. The low and moderately high resistive portions at a depth of 3.97 - 17.7 m on the 2D ERT section coincide effectively with the weathered layers on the geolectric sections indicating these layers/zone to be the weathered and hydrogeologic unit of the study area incompetent for engineering infrastructural foundations for sustainable development of infrastructures in the area.

The fifth layer (layer 5) comprise of fresh basement with resistivity value of 1434.2  $\Omega$ m and thickness of about 80 m beneath the surface. The very high resistive portions with resistivity range of 900 - 1211  $\Omega$ m on the 2D ERT section also coincide effectively with the very high resistive portions on the VES section, indicative of fresh basement bedrock zone suitable for the construction of any form of engineering foundation for sustainable development of infrastructures in this area of study.

#### 4.0 CONCLUSION

The integration of Vertical Electrical Sounding (VES) and 2D Electrical Resistivity Tomography (ERT) techniques in delineating the depth to competent rock for sustainable foundation development of engineering infrastructure in the study areas was successfully carried out. Considering the results from the two electrical resistivity techniques adopted in the study, it was too obvious that the two techniques were so efficient and also effective in the subsurface characterization for infrastructural sustainable development. The results from the study revealed that the subsurface in these areas were characterized by the presence of both weak and competent geological structures, uneven bedrock topography, deep and shallow weathering/fracturing bedrocks and saturated clay/shale zones classified as the hydrogeologic units (groundwater potential zone) of their areas viable for groundwater exploration and development.

The competent zones are recommended for the sustainable development of any form of infrastructures in the study areas. Precautionary measures are also recommended especially in the weathered and partially weathered zones during planning/designing and construction processes to mitigate possible risk of differential settlement, subsurface subsidence and other foundational issues associated with building on concealed weak geological subsurface features/structures/formations.

#### CONFLICT OF INTEREST

The authors declared no conflict of interest.

#### REFERENCES

- Adegbola, R. B., Oseni, S. O., Sovi, S. T., Oyedele, K. F. and Adeoti, L. (2010). Subsurface characterization and its environmental implications using the electrical resistivity survey: Case with LASU foundation programme campus Badagry, Lagos state, Nigeria. *Nature and Science*, 8(8): 146 - 151.
- Adebo, B. A., Layade, G. O., Ilugbo, S. O., Hamzat, A.A. & Otoberise, H. K. (2019). Mapping of Subsurface Geological Structures using Ground Magnetic and Electrical Resistivity Methods within Lead City University, Southwestern Nigeria. *Kada Journal of Physics* 2(2). 64-73.
- Adebo, B. A., Makinde, O. E. & Ilugbo, S. O. (2021). Application of Electrical Resistivity Method to Site Characterization for Construction Purposes at Institute of Agriculture Research and Training Moor Plantation Ibadan. *Indonesian Journal of Earth Sciences*, 1(2). (2021): 49-62.
- Ademila, O. (2022). Combined geophysical and geotechnical investigation of pavement failure for sustainable construction of Owo-Ikar Highway, Southwestern Nigeria. *National Research Institute of Astronomy and Geophysics (NRIAG) journal of Astronomy and Geophysics*. 10(1):183-201. doi: 10.1080/20909977.2021.1900527.
- Aigbedion, I., Bawallah, M. A., Ilugbo, S. O., Abulu, F. O., Eguakhide, V., Afuaman, E. W., & Ukubile, B., (2019). Geophysical Investigation for pre-foundation studies at RCCG, Calvary Love Parish 2, Ukpenu, Ekpoma, Edo state, Nigeria. *International Journal of Research and Innovation in Applied Science*, 4(5), 39 - 45.
- Alile, O. M., Ujuanbi, O., & Evbuomwan, I. A., (2011). Geoelectric investigation of groundwater in Obaretin-Iyanomon locality, Edo state, Nigeria. *Journal of Geology and Mining Research* 3(1), 13 - 20. <https://www.academicjournals.org/jgmr>.
- Aning, A. A., Asare, V. S., Wemegah, D. D., Noye, R. M., Preko, K., & Danuor, S. K. (2019). Integrated Geophysical and Geological Mapping of the Lithological and Geological Structures at a Proposed Generator Site. *Journal of Geoscience and Environment Protection*. 7, 73-85. <https://doi.org/10.4236/gep.2019.712005>
- Amadi, A., Eze, C., Igwe, C., Okunlola, I., Okoye, N., (2012). Architect's and geologist's view on the causes of building failures in Nigeria. *Modern Applied Science* 2012: 6(6): 31.
- Aydan, O., Ulusay, R., & Tokashiki, N. (2014). A new rock mass quality rating system: Rock mass quality rating (RMQR) and its application to the estimation of geomechanical characteristics of rock masses. *Rock Mechanics and Rock Engineering*, 47(4), 1255-1276, <https://doi.org/10.1007/s00603-013-0462-t>.
- Ayininuola, G. and Olalusi, O. (2004). Assessment of Building Failures in Nigeria: Lagos and Ibadan Case Study. *African Journal of Science and Technology* 5(1).
- Ayolabi, E. A., Ibon, E. J. and Folorunsho, A. F. (2012a). engineering site Characterization using 2-D and 3-D Electrical Resistivity Tomography in Star Dust Residential Estate Gbagada, Lagos state Nigeria. *journal of Geology and Mining Research*, 3(12). 140-142.
- Ayolabi, E. A., Folorunso, A. F. and Jegede, O. E. (2012b). An application of 2D electrical resistivity tomography in geotechnical investigations of foundation defects: A case study in Ogudu, Lagos State Nigeria. *Journal of Geology and Mining Research*, 3(12), 142-151. <http://www.academicjournals.org/jgmr>. DOI: 10.5897/JGMR12.002.

- Ayuk, A. M., Olayanju, G. M. and Adelusi, A. O. (2005). Use of electrical resistivity technique for engineering site investigation: A case study from Ado-Ekiti, South-western Nigeria. *Global Journal of Pure and Applied Sciences*. 11(4). 543-552.
- Bawallah, M. A., Ilugbo, S. O., Aigbedion, I., Aina, A. O. & Oyedele, A. A. (2019b). Modeling of subsurface integrity using Dar-Zarrouk parameters: A case study of Ikekogbe UBE Primary School, Ekpoma, Edo State, Nigeria. *Journal of Geography, Environment and Earth Science International*. 22(1). 1-17.
- Bawallah, M. A., Oyedele, A. A., Ilugbo, S. O., Ozegin, K. O., Ojo, B. T., Olutomilola, O. O., Airewele, E. & Aigbedion, I. (2020). Evaluation of structural defects and the dynamic of stress and strain on a building along Oluwole Area. Southwestern Nigeria. *Applied Journal of Physical Science*, 2(2), 23 - 37.
- Burger, H. R., Sheehan, A. F., & Jones, C. H., (2006). Introduction to applied geophysics: exploring the shallow subsurface. TN269.B86.2006; 622'.15-dc22. w.w. Norton & Company. Inc., 500 Ffth Avenue, New York, N. Y. 10110, [www.wwnorton.com](http://www.wwnorton.com).
- Dahlin, T., & Zhou, B. (2002). A numerical comparism of 2D resistivity imaging with 10 electrode arrays. *Geophysical Prospecting*, 52(5), 379-398.
- Dahlin, T. and B. Zhou, (2002). Gradient and Mid-point referred measurements for multichannel 2-D resistivity imaging, Procs. 8th meeting of the environmental and engineering geophysics, Aveiro, Portugal 8-12 September 2002, 157 - 160.
- Dimuna, K. O., (2010). Incessant incidents of building collapse in Nigeria. A challenge to Stakeholders. *Global Journal of Researches in Engineering 2010*. 10(4): 75 - 84.
- Ede, A. N., (2010). Building collapse in Nigeria. The trend of casualties in the last decade (2000-2010). *International Journal of Civil & Environmental Engineering*, 10(6), 32 - 42.
- Ede, A. N., (2011). Measures to reduce the high incidence of structural failures in Nigeria. *Journal of Sustainable Development in Africa 2011*: 13(1): 153 - 161.
- Ellingwood, B. R. and Dusenberry, D. O., (2005). Building design for abnormal loads and progressive collapse. *Computer-Aided Civil and Infrastructure Engineering 2005*: 20(3): 194-205.
- Ilugbo, S. O., Adebo A. B., Ajayi, O. A., Adewumi, O. O. & Edunjobi, H. O. (2018b). Geophysical and geotechnical studies of a proposed structure at Akure, Southwestern Nigeria. *Journal of Engineering Research and Reports*. 2(2). 1-12.<https://doi.org/10.9734/jerr/2018/v2i29910>.
- Koefoed O. A. (1979). Direct methods of interpreting resistivity observations. *Geophysical Prospecting*, Vol 13(4): 568 - 591.
- Karous, M. and Pernu, T. K., (1985). Combined Sounding-Profiling Resistivity Measurements with three-electrode arrays. *Geophysical Prospecting*, 33(3), 447 - 459. <https://doi.org/10.1111/j.1365.2478.1985.tb00445>.
- Lech, M., Skutnik, Z., Bajda, M., and Markowska-Lech, K. (2020). Applications of Electrical Resistivity Surveys in Solving Selected Geotechnical and Environmental Problems. *Applied Sciences*, 10(7), 2263. <https://doi.org/10.3390/app10072263>.
- Loke, M. H., (1994). The inversion of two-dimensional resistivity data. Unpublish. PhD thesis, Uni. of Birmingham.
- Loke, M. H. and Barker, R. D., (1996). Practical techniques for 3D resistivity surveys and data inversion 1. *Geophysical Prospecting*. 44(3), 499-523.
- Loke, M. H. and R. D. Barker., (1996). Rapid least square inversion of apparent resistivity pseudosection using a quasi-Newton method. *Geophysical prospecting*, pp 131 - 152.
- Loke, M. H., Chambers, J. E., Rucker, D. F., Kuras, O., Wilkinson, P. B., (2013). Recent developments in the direct-current geoelectrical imaging method: *Journal of Applied Geophysics*, 95, 135-156, doi: 10.1016/j.jappgeo.2013.02.017.

- Luna, R. and Jadi, H. (2000). Determination of dynamic soil properties using geophysical methods. *Pro. Ist Int. Conf. on the Application of Geophysical and NDT Methodologies to Transportation Facilities and Infrastructure Geophysics (Federal Highway Administration, Saint Louis, MO). Vol 3, pp. 1-15*
- Onyebueke, E., Manzi, M., Durrheim, R., (2018). High-Resolution Shallow Seismic integrated with Electrical Resistivity Method for hydrogeological Prospecting in 24th European Meeting of Environmental and Engineering Geophysics (vol. 2018, No. 1, pp.1-5) European Association of Geoscientists & Engineers.
- Onyebueke, E. O., Durrheim, R. J., Manzi, M. S. D., Sebothoma, S., Zhang, S. E. and Stettler, E. (2020). High-resolution Integrated Geophysical Investigation at the Lancaster Gold Mine, Krugersdorp, South Africa. *Pure and Applied Geophysics*. Springer Nature Switzerland AG. <https://doi.org/10.1007/s00024-020-02529-6>.
- Onyebueke, E. O., Manzi, M. S., Rapetsoa, M. k., & Westgate, M. (2021). In-mine Underground Tunnel Seismic Experiment, Using High- Resolution Reflection Seismic Method at Maseve Mine, Rustenburg, South Africa. In 82nd EAGE Annual Conference and Exhibition (Vol. 2022, No. 1, PP. 1 - 5). European Association of Geoscientists and Engineers.
- Onyenweife, G. I., Nwozor, K. K., Onuba, L. N., Omezi I. and Okoronkwo U. E. (2024) Assessment of Subsurface Sustainability for Civil Engineering Structures in Awka North, Anambra State Southeast Nigeria, Using Electrical Resistivity Method *Int. J. Innovative Environ. Studies Res.* 12(4):9-22, DOI:10.5281/zenodo.13988698
- Onyenweife, G. I., Nwozor, K. K., Okoronkwo, U. E. and Omezi, I. (2024) Aquifer Delineation and Subsurface Investigation for Engineering Structures in Parts of Awka North, Anambra State Nigeria, Using Vertical Electrical Sounding Method, *International Journal of Innovative Environmental Studies Research* 12(4):23-49. DOI:10.5281/zenodo.14007873
- Onyenweife, Geraldine Ifesinachi, Ben-Owope, Ogechukwu Anastasia and Nwozor, Kingsley Kanayo (2025). Evaluation of Petrophysical and Geomechanical Analysis of Subsurface Geological Information for Sustainable Groundwater and Engineering Development in Parts of Anaocha Local Government, Anambra State, Nigeria, *Asian Journal of Geographical Research, Volume 8, Issue 3, Pp. 153-162*.
- Olayanju, G. M. Mogaji, K. A. Lim. H. S., & Ojo, T. S. (2017). Foundation integrity assessment using integrated geophysical and geotechnical techniques: Case study in crystalline basement complex, southwestern Nigeria. *journal of Geophysics and Engineering*, 14(3), 675-690.
- Orellana E. and Mooney H. M. (1972). Master tables and curves for vertical electrical sounding over layered structures. Inteciends, Madrid; 1966.
- Osazuwa, I. B., and Chii, E., (2010). Two-Dimensional electrical resistivity survey around the periphery of an artificial lake in the Precambrian basement complex of Northern Nigeria. *International Journal of Physical Sciences*, 5(3):238-245.
- Othman, A. A. (2005). Construed geotechnical characteristics of foundation beds by seismic measurements. *J. Geophys. Eng.* 2 126-38.
- Oyedele, K. F. and Olorode. D. O. (2010). Site Investigation of Subsurface Conditions Using Electrical Resistivity Method and Cone Penetration Test at Medina Estate, Gbagada, Lagos, Nigeria. *world Applied Sciences Journal* 11(9): 1097-1104, 2010.
- Oyedele, A. A., Bawallah, M. A., Ozegin, K. O., Ilugbo, S. O., Ajayi, C. A. & Aigbedion, I. (2020). Probability functions of road failures in a typical basement complex region, South-western Nigeria: A case study of Akure-Oba Ile Airport Road. *International Journal of Water Resources and Environmental Engineering*. 12(2), 10-21. <https://doi.org/10.5897/IJWREE2019.0906>.
- Oyedele, A. A., Bawallah, M. A., Ozegin, K. O., Ilugbo, S. O., Ajayi, C. A. & Aigbedion, I. (2020). Probability functions of road failures in a typical basement complex region, South-western Nigeria: A case study of Akure-Oba Ile Airport Road. *International Journal of Water Resources and Environmental Engineering*. 12(2), 10-21. <https://doi.org/10.5897/IJWREE2019.0906>.

- Petrit, K., Klamthim, P. and Duerrast, H. (2018)., 3D resistivity survey for shallow subsurface fault investigations. E3S Web of Conferences 34, 01007 (2018). <https://doi.org/10.1051/e3sconf/20183401007>.
- Soupios P., Papazachos C. B., Vargemezis G. and Savvaidis A. 2006. In situ geophysical investigation to evaluate dynamic soil properties at the Ilarionas Dam, Northern Greece Proc. *2nd int. Conf. Advances in Mineral Resources Management and Environmental Geotechnology (Hania, Crete, Greece, 25-27 September 2006) (Heliotopos Conference)* pp 149-56.
- Soupios, P. M. Georgakopoulos, P. Papadopoulos, N. Saltas, V. Andreadakis, A. Vallianatos, F. Sarris, A. and Makris, J. P. (2007). Use of engineering geophysics to investigate a site for a building foundation. *J. Geophys. Eng.* 4(2007) 94-103.
- Sonawane, S. G., Saner, A.B., Desale, H. S., and Joshi, S. R. (2023). Application of Electrical Resistivity in Site Investigation at Ground Profile. In A. K. Agnihotri. K. R. Reddy, & H. S. Chore (Eds.), *Proceedings of Indian Geotechnical and Geoenvironmental Engineering Conference (GGEC) 2021. Vol. 1(Vol. 280.pp.73-82).* Springer Nature Singapore. [https://doi.org/10.1007/978.981.19.4739-1\\_7](https://doi.org/10.1007/978.981.19.4739-1_7).
- Soupios, P. M. (2007). Use of engineering geophysics to investigate a site for a building foundation. *Journal of Geophysics. Eng.* 4 (2007): 94 - 103.
- Soupios, P., Papadopoulos, N., Papadopoulos, I., Kouli, M., Vallianatos, F., Sarris, A., Manios, (2007). Application of integrated methods in mapping waste disposal areas, in: *Environmental Geology.* 661 - 675. <https://doi.org/10.1007/s00254-007-0681-2>.
- Terzaghi, K., Perk, R. B., & Mesri, G. (1996). Soil mechanics in engineering practice. John wiley & sons.
- Venkateswara, V. R., Srinivasa, R., Prakasa, R. B. S. and Koteswara, R. P. (2004a). Bedrock investigation by seismic refraction method- a case study. *J. Ind. Geophys. Union* 8 223-8.
- Zohdy, A. A. R. (1964). Use of Dar Zarrouk Curves in the interpretation of vertical electrical sounding data. U. S. Geol. Survey. Bull., 1313-D: p.4.
- Zohdy, A. A. R., (1964). Earth resistivity and seismic refraction investigation in Clara Country, California, PhD thesis (unpublished), Stanford University, 131 – 135