Geoelectrical investigation of soils as foundation materials in Umudike area, Southeastern Nigeria

Geoelectrical investigation of soils in Umudike area of Abia State was undertaken in order to determine the competence of the soils as foundation materials. A total of 18Vertical Electrical Sounding (VES), using Schlumberger configuration was carried out. The results revealed three to six distinct geoelectric sequences with resistivities ranging from about 8Ωm to about 38,000Ωm and a variation in topsoil thicknesses with the least as 0.2m at vicinity of VES Station 2 Ahiaeke and the highest as 5.0m at VES Station 14 MOUAU. The topsoils are composed of sands, silts, sandy clays, clays and laterites. The study also revealed the cause of frequent cracking and collapse of a portion of the Umuahia-Ikot-Ekpene road. Based on the results of the survey, the most competent soils within which large civil engineering structures will be founded within the study area are encountered at VES 8,9 (inside ABSUPAC), 6 (opposite GCU), 14 and 15 (inside MOUAU).

Key words: Competent soils, Electrical Resistivity, Foundation failure, Geoelectric layer.

.

INTRODUCTION

The use of shallow geophysical methods of investigation in civil and construction engineering for road and building construction and evaluation, dam safety, and solution of related problems; engineering and environmental geophysics is defined as geotechnical geophysics (Sheriff, 2001). High rising buildings are among large civil engineering structures that are subjected to strong dynamic and static loads; and since the statistics of failures of building structures throughout the nation has increased geometrically; therefore the design and construction should be preceded by adequate investigation in order to prevent such failures. These failures have been attributed to a number of factors such as inadequate information about the soil and the subsurface geological material, poor foundation design and poor building materials.

The need for pre-foundation studies is therefore necessary in order to prevent loss of valuable lives and properties that always accompany such failure.

Foundation study usually provides subsurface information that normally assists civil engineers in designing the foundation of civil engineering structures. This is because some earth materials due to their nature cannot support solid and rigid structures; among these materials are clays and clay-bearing earth.

Similarly, earth materials such as sands and fresh basement rock provide firm support for solid foundation.

To this end, geophysical methods together with or besides other geotechnical approaches are routinely used for foundation investigation (Ajayi et al., 2005; Akinrinmade, 2013; Akintorinwa, 2009; Tabwassah and Obiefuna, 2012).

Geophysical methods such as the Electrical Resistivity (ER), Seismic Refraction, Electromagnetic (EM), Magnetic and Ground Penetrating Radar are used singly or in combinations for engineering site investigation (Olorunfemi and Meshida, 1987; Fatoba et al., 2010; Hunter et al., 2011; Melikan, 1960; Olorunfemi et al, 2000, 2004; Oluwakemi and Michael, 2011). The applications of such geophysical investigation are in the determination of layer thickness, depth to bedrock, structural mapping and evaluation of subsoil competence. The need to provide information in the subsurface sequence and structure disposition necessary for foundation design necessitated a geoelectrical investigation of the soils of Umudike area and environs as foundation materials.

Geologically, there are about 11 different formations in Abia State of Nigeria, and the selected study area (Umudike and its environs) falls within the transition zone of Ogwashi Formation and Coastal plain sands (Fig. 1). Within a transition zone, there are at times abrupt or gradual changes in lithology; therefore a complex overall situation with respect to defining the competence of near-surface formation as foundation materials could arise in future as a result of attempts in the construction of high rising buildings.

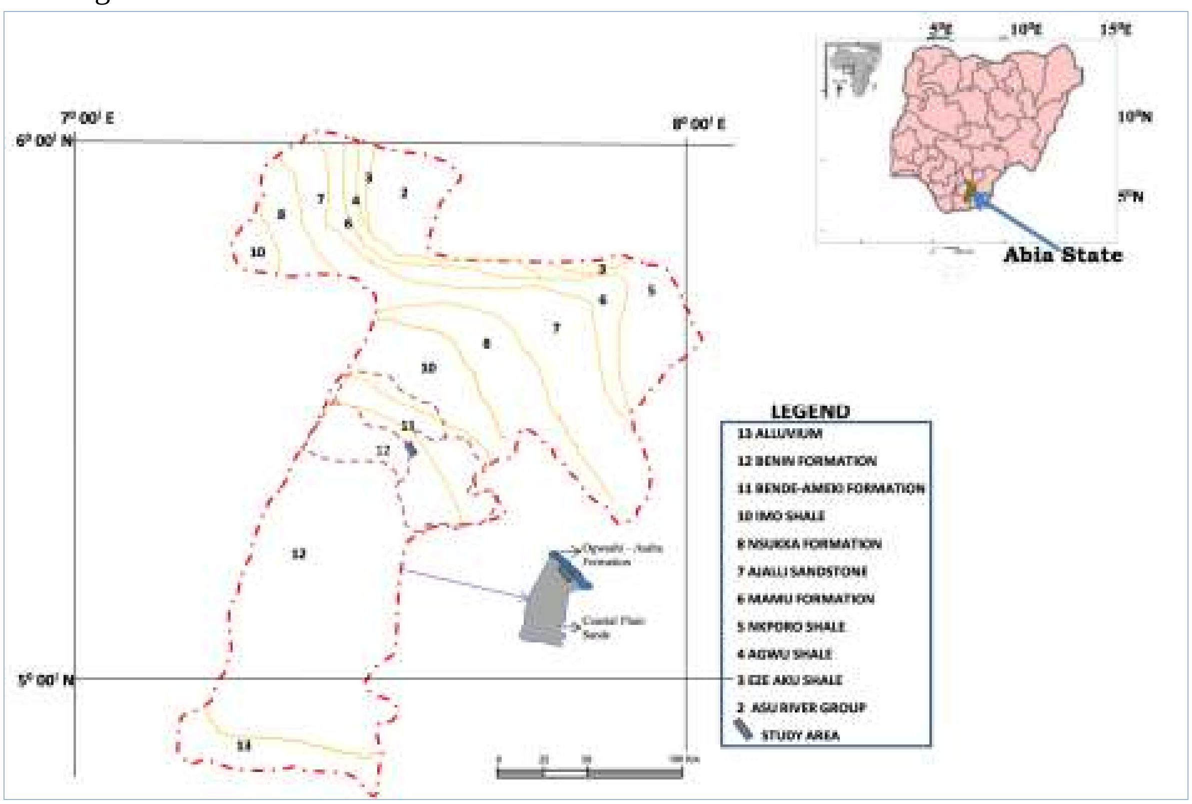

Fig. 1: Geologic map of Abia State of Nigeria showing the study area (Modified after GSN, 1985).

Ogwashi Formation and Coastal Plain Sands are situated in the Cenozoic Niger Delta Basin. The Cenozoic Niger Delta is situated at the intersection of the Benue Trough and the South Atlantic Ocean where triple-R junction (rift system) developed during the break-up of Gondwana leading to the separation of the continents of South America and Africa in the Late Jurassic. The third arm of the rift after extending to about 1000km northeast from the Gulf of Guinea to Lake Chad failed (aulacogen), thus forming the Benue Trough (Stoneley, 1966).

Subsequently sediments from weathering of the basement uplift were deposited into the trough through rivers and lakes by Early Cretaceous (Murat, 1972). By Mid-Cretaceous onwards Marine sedimentation took place in the Benue Trough; thus making it possible in conjunction with other geologic events for it to be presently underlain by diverse sedimentary basins.

The Benue Trough is arbitrarily divided into the Lower, the Middle and the Upper Benue Trough; and by Santonian times the area underwent intense folding and compression forming many anticlines and synclines.

After the Santonian-Campanian tectonism which formed the Abakiliki anticlinorium, the western margin of the Lower Benue Trough subsided, and the corresponding synclinorium became the Anambra basin where over 2500m of deltaic complexes accumulated. However by Eocene, the inception of Tertiary Niger Delta Basin commenced. Thus, the Late Cretaceous deltaic sedimentation in the Anambra Basin was followed by the shift in deltaic deposition southward and consequently the construction or outbuilding of the Niger Delta took place. The interplay between subsidence and deposition arising from a succession of sea transgressions and regressions (Hospers, 1965) gave rise to the deposition of three lithostratigraphic units in the Niger Delta (Short and Stauble, 1967).These units are Marine Akata Formation, Paralic Agbada Formation, and the Continental Benin Formation. The delta has prograded a distance greater than 250km from the Benin and Calabar flanks to the present delta front. Average thickness of sediments in the Niger-Delta is about 12,000m with an area of about 140,000km^2 (Obaje, 2009).

Ogwashi Formation was grouped as the upper member of the Ameki (Agbada Group) Formation (Short and Stauble, 1967). In the grouping, the coastal plain sands of (Reyment, 1965) were referred to as Benin formation (Table 1).

Table 1: Stratigraphic correlation chart of eastern Niger Delta outcrops and their subsurface equivalents (Short and Stauble, 1967)

YOUNGEST KNOWN AGE		OLDEST KNOWN AGE	YOUNGEST KNOWN AGE		OLDEST KNOWN AGE
RECENT	**BENIN FORMATION** Afam Shale Member	OLIGOCENE	PLIO/ PLEISTOCENE	**BENIN FORMATION**	MIOCENE ?
RECENT	**AGBADA FORMATION**	EOCENE	MIOCENE	**OGWASHI-ASABA FORMATION**	OLIGOCENE
			EOCENE	**AMEKI FORMATION**	EOCENE
RECENT	**AKATA FORMATION**	EOCENE	L. EOCENE	**IMO SHALE FORMATION**	PALEOCENE
EQUIVALENTS NOT KNOWN			PALEOCENE	**NSUKKA FM**	MAESTRICHTIAN
			MAESTRICHTIAN	**AJALI FORMATION**	MAESTRICHTIAN
			CAMPANIAN	**MAMU FORMATION**	CAMPANIAN
			CAMP./MAEST.	**NKPORO SHALE**	SANTONIAN
			CONIACIAN/ SANTONIAN	**AWGU SHALE**	TURONIAN
			TURONIAN	**EZE AKU SHALE**	TURONIAN
			ALBIAN	**ASU RIVER GROUP**	ALBIAN

While (Amajor, 1986) grouped the Ogwashi Formation as the lower member of the Benin Formation, and the coastal plain sands as the upper member (Table 2).
Ogwashi Formation is predominantly sandy with alternating lignite seams and a few beds of clay with sparse marine fauna (Reyment, 1965; Short and Stauble, 1967).

The Coastal plain sands are predominantly yellow and white sands alternating with pebbly layers and a few clay beds (Reyment, 1965).
The formation comprises of shale/sand sediments with intercalation of thin clay beds (Asseez, 1976; Murat, 1972).
The sands are mostly medium to coarse grained, pebbly, moderately sorted with local lenses of poorly cemented sands and clays. Petrographic analysis indicates that the composition of the rocks is as follows: 95-99% Quartz grains, 1-2.5% of Na+K-mica (Onyeagocha, 1982).

Table 2: Stratigraphic correlation chart of the Niger Delta (After Amajor, 1986)

AGE	SURFACE OUTCROP EQUIVALENT FORMATIONS		SUBSURFACE FORMATIONS	MEGA-DEPOSITIONAL ENVIRONMENTS
PLIOCENE-RECENT	COASTAL PLAIN SANDS		BENIN FM	PARALIC CONTINENTAL
MIOCENE-RECENT	OGWASHI-ASABA FM	IJEBU FM	AFAM CLAY MBR-	CONTINENTAL DELTA PLAIN
EOCENE-RECENT	AMEKI FM	ILARO FM OSHO-SHUN FM	AGBADA FM	PARALIC DELTA FRONT
PALEOCENE-RECENT	IMO FM	EWEKORO FM	AKATA FM	MARINE PRODELTA
CAMPANIAN-MAASTRICHTIAN SANTONIAN	NSUKKA FM AJALI SST MAMU FM NKPORO-ENUGU SHALE			UPPER CRETACEOUS PRO NIGER DELTA SUCCESSION

The selected study area (Umudike and its environs) is located within the central parts of Ikwuano-Umuahia area; and lies within latitudes 5^0 28.793'N and $5^0$34.661'N, and longitudes 7^0 31. 602' E and $7^0$34. 661' E (Fig 2).

Climate of the area is the sub-equatorial climatic belt with tropical rain-forest vegetation. The mean annual temperature is between 24^0C and 27^0C; while the annual rainfall varies between 1500mm and 3500mm (Adeleke and Leong, 1978).

Institutions and research centres such as Forestry Research Institute, New Industrial Market, Soil and Water Department of Federal Ministry of Agriculture and Rural Development, and Government College Umuahia (GCU) are situated within the study area.
Others are Abia State University Practical Agricultural Campus (ABSUPAC), National Root Crops Research Institute (NRCRI) and Michael Okpara University of Agriculture(MOUAU).
The area is witnessing rapid increase in population and subsequently expansion in infrastructure.
It is known that rapid industrialization, urbanization and population growth have attendant pressure on all sustainable resources.
This has led to many geophysical groundwater investigations in the area but not much have been done in the area of foundation investigations.
The land is fixed but there is daily increase in infrastructure. Also, the reduction in available land due to increasing infrastructure will eventually give rise to the need of optimally using the available ones for sustainable practices.

In light of this, Umudike area and its environs are gradually being faced with the consequent attempts in the construction of high rising buildings

It is therefore essential to assess the foundation competence of the near-surface soil and subsurface geological materials.

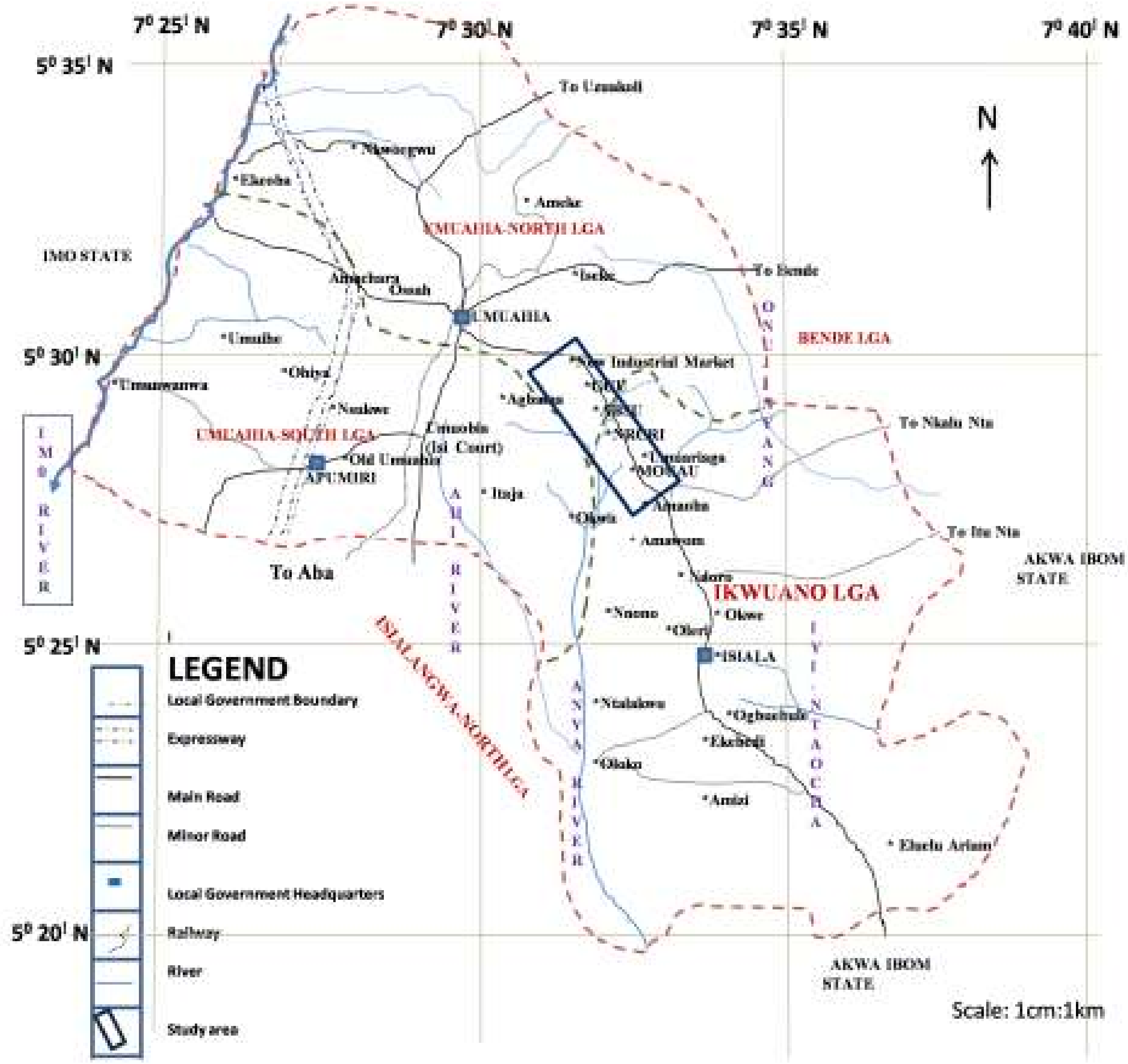

Fig. 2: Map of Ikwuano-Umuahia area of Abia State showing the study area

METHODOLOGY

The instruments used in the geoelectrical survey include resistivity meter (ABEM SAS 4000 Terrameter), Geographic Positioning System (GPS), 12Volts heavy duty motor battery with two connecting wires with crocodile clips, four hammers and four electrodes with rolls of wire, two rolls of 100m rope each, Three rods for ropes (one central and two end ones), One big umbrella for shade, Data sheets with K-values and writing pen.

Six traverses were established across the study area (Fig. 3). Three (3) Vertical Electrical Sounding (VES) stations were occupied along each of the traverses and a total of 18 soundings were carried out using the Schlumberger electrode configuration of maximum half current electrodes spacing (AB/2) of 65m (Table 3, Fig. 4).

Table 3: VES stations and their localities in the study area

Data Number	Data Location	GPS Reading		
		Elevation (m) a.m.s.l	**Latitude °N**	**Longitude °E**
1	Umuohu-Azueke (Ministry of Agriculture)	186.5	$5^{0}34.623'$ N	$7^{0}34.661'$ E
2	Umuohu-Azueke (New Industrial Market)	135.4	$5^{0}30.558'$ N	$7^{0}32.004'$ E
3	Umuohu-Azueke (New Industrial Market)	148.9	$5^{0}30.318'$ N	$7^{0}31.602'$ E
4	Umuohu-Azueke (Government College Umuahia)	131.5	$5^{0}30.134'$ N	$7^{0}32.233'$ E
5	Umuohu-Azueke (Government College Umuahia)	151.2	$5^{0}30.070'$ N	$7^{0}32.268'$ E
6	Umuohu-Azueke (Igbugbo Opposite GCU)	162.5	$5^{0}34.645'$ N	$7^{0}32.564'$ E
7	Umudike (Ihiuzo American Quarters Plantation)	147.0	$5^{0}29.560'$ N	$7^{0}32.323'$ E
8	Umuohu-Azueke (Abia State University)	137.9	$5^{0}28.645'$ N	$7^{0}33.721'$ E
9	Umuohu-Azueke (Behind Abia State University)	123.0	$5^{0}29.732'$ N	$7^{0}32.334'$ E
10	Umudike (Behind NRCRI)	98.3	$5^{0}28.877'$ N	$7^{0}32.411'$ E
11	Umudike (Inside NRCRI)	107.5	$5^{0}28.859'$ N	$7^{0}32.432'$ E
12	Umudike (V.C’S Lodge)	126.3	$5^{0}29.312'$ N	$7^{0}32.761'$ E
13	Umuariaga (Opposite MOUAU)	129.4	$5^{0}28.881'$ N	$7^{0}33.052'$ E
14	Umudike (Inside MOUAU)	113.3	$5^{0}28.793'$ N	$7^{0}32.433'$ E
15	Umudike (Behind MOUAU)	159.3	$5^{0}29.521'$ N	$7^{0}32.445'$ E
16	Amaoba	199.4	$5^{0}29.421'$ N	$7^{0}32.445'$ E
17	Amaoba	172.7	$5^{0}29.633'$ N	$7^{0}32.544'$ E
18	Amaoba	190.1	$5^{0}29.655'$ N	$7^{0}32.632'$ E

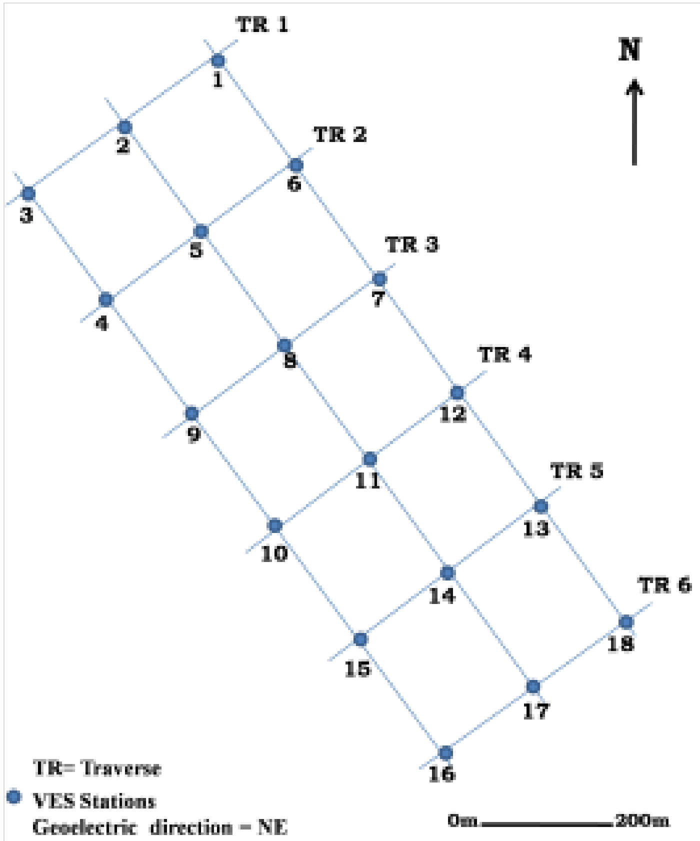

Fig. 3: Data acquisition grid of the study area showing the vertical electrical sounding stations

The 12V direct current (DC) served as current source to the Terrameter, and the current was passed into the subsurface through the two current electrodes ‘AB’; while the two potential electrodes ‘MN’ were linearly arranged along the survey line to determine the ground potential difference (Fig. 4).

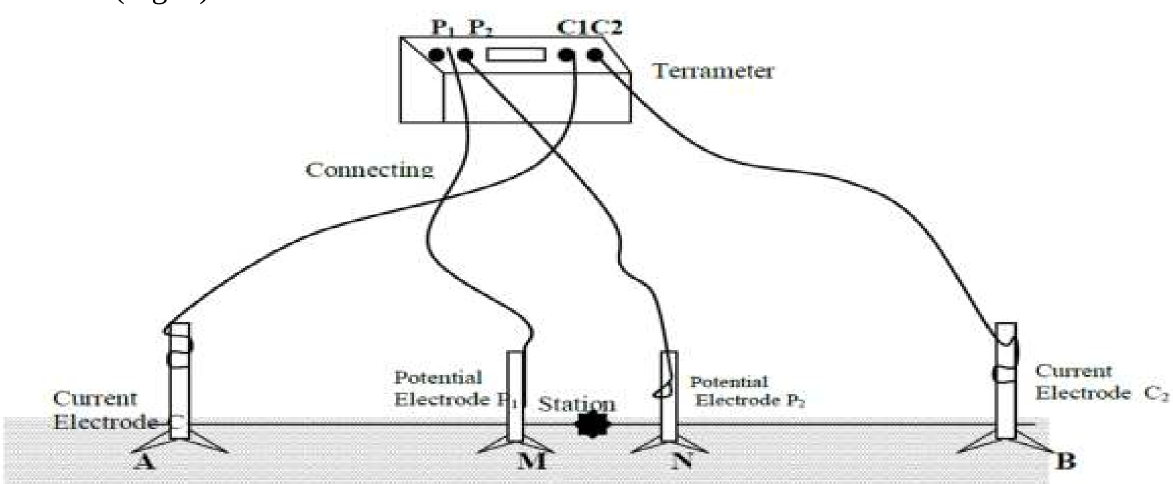

Fig. 4: Schematic diagram of the Schlumberger electrode configuration used.

The resultant ratio of the current and voltage is the measured data which is the ground resistance read off in the Terrameter.

This ground resistance is used in computing the apparent resistivity using the corresponding k-values with the formula:

$$\rho a = kR \qquad \text{. . . equation (1)}$$

where ρ_a = Apparent resistivity, $k = \pi\left(\frac{L^2 - l^2}{2l}\right)$ = Geometric factor, R = Resistance in ohms L = AB/2 = Half current electrode spacing (m), *l* = MN/2 = Half potential electrode spacing (m).

Substituting the values of *k* into equation (1), we get

$$\rho a = \pi R\left(\frac{L^2 - l^2}{2l}\right) \qquad \text{. . . equation (2)}$$

The apparent resistivity values were plotted against electrode spacing (AB/2) on a bi-logarithmic graph sheet to generate depth sounding curves. The curves were then inspected visually for identification of the curve types; and subsequently used for the conventional partial curve matching technique and use of auxiliary point diagrams (Zohdy, 1989). From the result, estimates of the resistivity and thickness of the various geoelectric layers were obtained and used for computer iteration using RESIST version 1.0 software (Varder -Velpen, 1988).

Finally, interpreted results were used for the analysis of sounding curves and preparation of geoelectric sections.

RESULTS AND DISCUSSION

4.1.1 Analysis of Sounding Curve

Table and curves for vertical electrical sounding over layered structures is a function of the electrode configuration together with the resistivities and thicknesses of the layers (Orellana and Mooney, 1966; Zohdy, 1989; Amos-Uhegbu et al., 2012). Sounding (VES) curves are obtained by plotting the calculated apparent resistivity against the corresponding half current electrode separation (AB/2), and the letters Q,A,K and H are used to indicate the variation of resistivity with depth (Fig. 5).

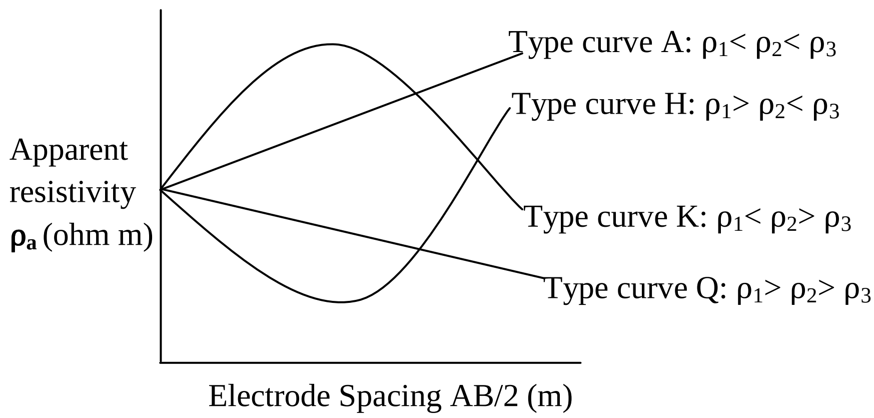

Fig. 5: Schematic diagram of resistivity type curves for layered structures.

Fourteen curve types were identified within the study area, and the number of layers varies between three layers and six layers with five-layered type curves predominant. Resistivity type curves for some locations in the study area are as displayed (Fig. 6 to Fig. 9). While, Table 4 is a profile of the VES data and location points in the study area.

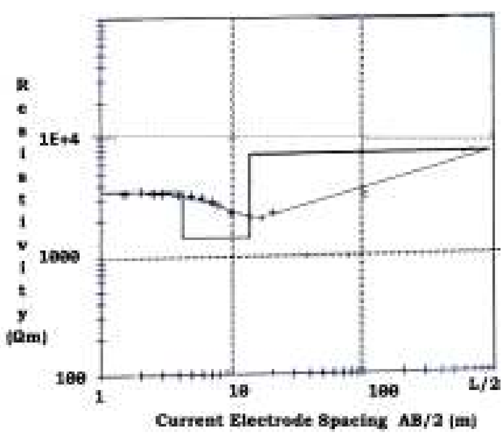

Fig. 6: Resistivity curve of VES 6 (Igbugbo Opposite GCU).

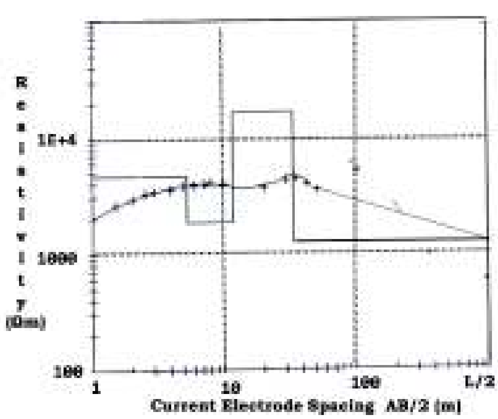

Fig. 7: Resistivity curve of of VES 2 at New Industrial Market.

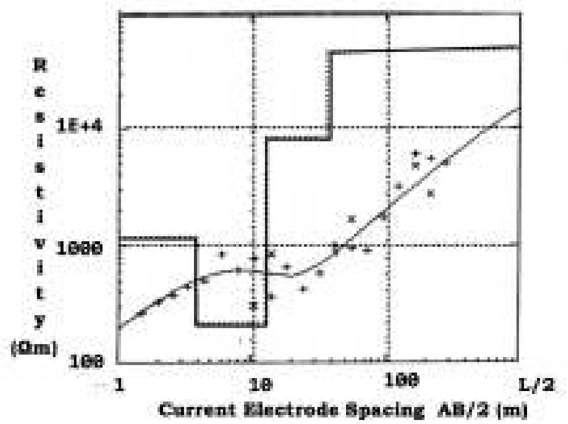

Fig. 8: A computer modelled curve of VES 17 at Amaoba

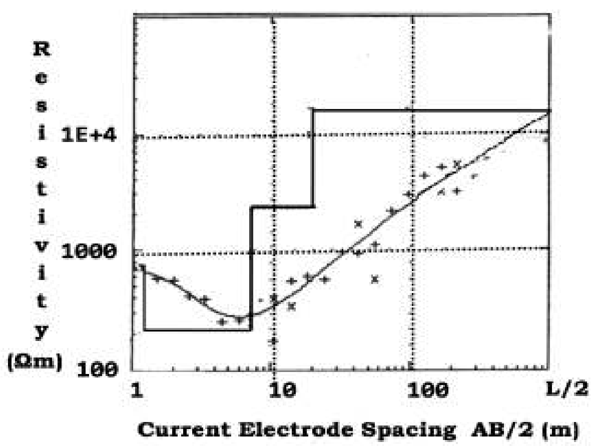

Fig. 9: A computer modelled curve of VES 11 infront of NRCRI

Table 4: A profile of VES data of the various sounding stations in the study area.

VES Nos.	Resistivity of layers (Ωm)	Thickness of layers (m)	Type Curve
VES 1	ρ_1 = 332 ρ_2 = 1786.9 ρ_3 = 1250.9 ρ_4 = 640.9 ρ_5 = 3200.8	t_1 = 0.8 t_2 = 3.2 t_3 = 7.0 t_4 = 16.7 t_5 = ?	HKH
VES 2	ρ_1 = 563 ρ_2 = 1720.0 ρ_3 = 4680 ρ_4 = 1250 ρ_5 = 570	t_1 = 0.2 t_2 = 5.1 t_3 = 6.4 t_4 = 22.2 t_5 = ?	AKQ
VES 3	ρ_1= 187.7 ρ_2 =1626.3 ρ_3 =4867.6 ρ_4 = 231.7	t_1 = 0.6 t_2 = 4.8 t_3 = 15.1 t_4 = ?	AK
VES 4	ρ_1 =140.6 ρ_2 =8.3 ρ_3 =226.5 ρ_4 = 7147.3 ρ_5 =10197.5	t_1 = 0.8 t_2 = 1.8 t_3 = 1.4 t_4 = 22.2 t_5 = ?	HAA
VES 5	ρ_1 = 2200.0 ρ_2 = 950.0 ρ_3 = 3630.0 ρ_4 = 7710.0	t_1 = 0.4 t_2 = 6.5 t_3 = 25.2 t_4 = ?	HA
VES 6	ρ_1 = 3520.0 ρ_2 = 1460.0 ρ_3 = 7310.0	t_1 = 4.2 t_2 = 13.9 t_3 = ?	H
VES 7	ρ_1 = 114.0 ρ_2 = 1105.0 ρ_3 = 295.0 ρ_4 = 527.0	t_1 = 1.0 t_2 = 20.9 t_3 = 9.2 t_4 = ?	KH
VES 8	ρ_1 = 575.0 ρ_2 = 7370.0 ρ_3 = 519.0 ρ_4 = 12000.0 ρ_5 = 68.6	t_1 = 0.4 t_2 = 2.4 t_3 = 4.7 t_4 = 17.8 t_5 = ?	KHK
VES 9	ρ_1 = 5104.2 ρ_2 = 2568.2 ρ_3 = 845.1	t_1 = 3.1 t_2 = 28.1 t_3 = ?	Q
VES 10	ρ_1 =37999.0 ρ_2 = 65.4 ρ_3 = 666.8 ρ_4 = 51.0 ρ_5 = 3276.1 ρ_6 = 61,788	t_1 = 0.4 t_2 = 0.8 t_3 = 2.3 t_4 = 6.7 t_5 = 12.4 t_6 = ?	HKHQ
VES 11	ρ_1= 745.0 ρ_2 =220.2 ρ_3 =2370.6 ρ_4 = 16580.7	t_1 = 1.2 t_2 = 6.1 t_3 = 10.7 t_4 = ?	HQ
VES 12	ρ_1= 705.0 ρ_2 =15.0 ρ_3 =805.0 ρ_4 = 65810.7	t_1 = 1.2 t_2 = 1.6 t_3 = 2.8 t_4 = ?	HA
VES 13	ρ_1= 518.0 ρ_2 =878.0 ρ_3 =2768.0	t_1 = 0.6 t_2 = 15.0 t_3 = ?	A
VES 14	ρ_1= 945.0 ρ_2 = 3380.8 ρ_3 = 21000.0 ρ_4 = 7780.0	t_1 = 5.0 t_2 = 7.0 t_3 = 21.5 t_4 = ?	AK
VES 15	ρ_1= 4300.0 ρ_2 = 3200.0 ρ_3 = 400.0 ρ_4 = 30000.0 ρ_5 = 611.0	t_1 = 1.2 t_2 = 1.6 t_3 = 4.0 t_5 = 21.4 t_6 = ?	QHK
VES 16	ρ_1= 14.5 ρ_2 = 16.5 ρ_3 = 86875.0	t_1 = 1.2 t_2 = 1.6 t_3 = ?	A
VES 17	ρ_1= 132.0 ρ_2 = 1200.0 ρ_3 = 220.0 ρ_4 = 8400.0 ρ_5 = 46700.0	t_1 = 0.6 t_2 = 3.0 t_3 = 8.6 t_4 = 23.4 t_5 = ?	KHA
VES 18	ρ_1= 5130.0 ρ_2 =1400.0 ρ_3 =176.0	t_1 = 0.6 t_2 = 4.5 t_3 = ?	Q

4.1.2 Geoelectric sections of the study area

Subsurface resistivity is related to the physical property of interest such as lithology, porosity, water content etc; therefore electrical resistivity measurements determine subsurface resistivity distributions thereby differentiating layers based on resistivity values (Ako, 2002, Amos-Uhegbu et .al 2012).

Sounding curves obtained over a horizontally stratified medium could be presented as a descriptive profile displaying variation of apparent resistivity with depth (Zohdy, 1989). The profile is a scale drawing of the successive layer resistivities and thicknesses; so, a geoelectric section is a profile displaying variation of apparent resistivity with depth (Fig. 10, 11, and 12).

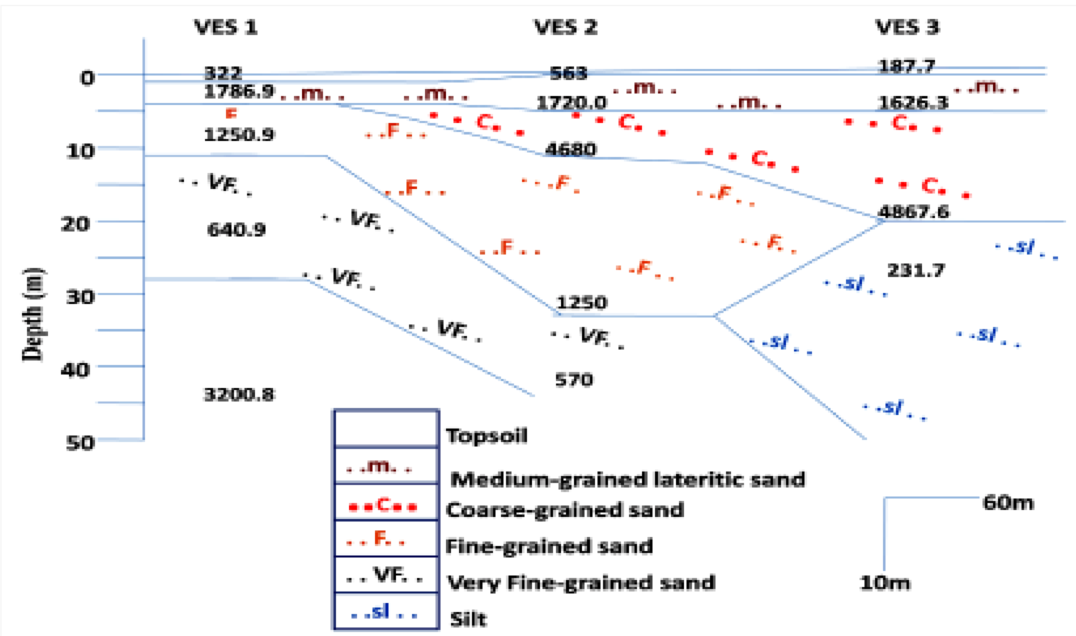

Fig. 10: Geoelectric sections along the first traverse

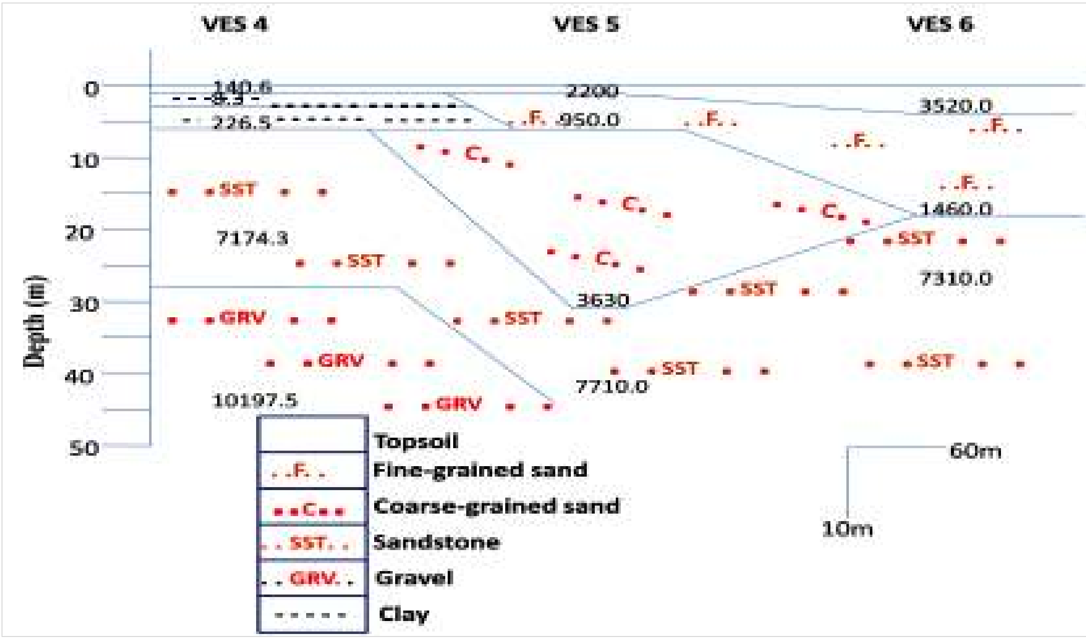

Fig. 11: Geoelectric sections along the second traverse

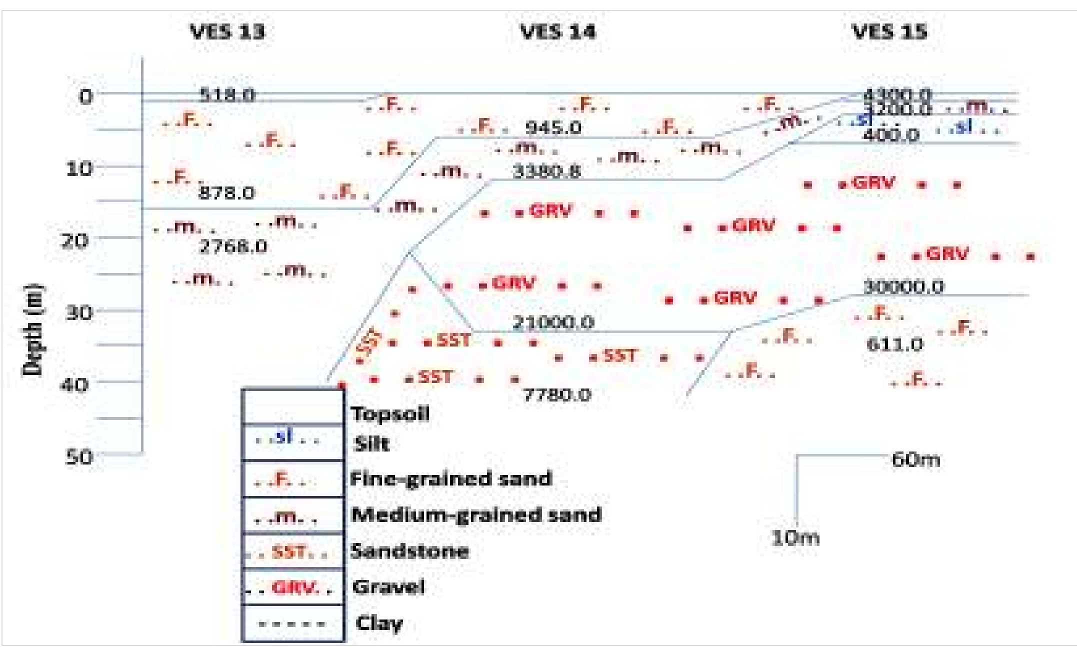

Fig. 12: Geoelectric sections along the fifth traverse

4.1.3 Subsurface Engineering Evaluation of the Study Area

Excavation for footings or foundation walls shall extend below depth of soil subjected to seasonal or characteristic volume change to undisturbed soil that provides adequate bearing capacity. So, topsoil is normally removed and variations in ground level corrected. Therefore, the best recommended depth of foundation is from 1.0 m to 1.5 m from original ground level (NHBC, 2011). The depth of foundation depends on some factors such as the availability of soil with adequate bearing capacity, depth of shrinkage and swelling as in case of clayey soils, due to seasonal changes which may cause appreciable movements; and the depth of frost penetration in case of fine sand and silt. Also, proximity of excavation and depth of ground water table are considered. Geoelectrical foundation engineering competence of soils can be qualitatively evaluated from layer resistivity; the higher the value of a layer resistivity, the higher the competence.

Amos-Uhegbu et.al (2012, 2014) extensively worked within the study area and lithologically deduced from drill-hole and geoelectric data that sediments with resistivity < 100Ωm are clays, 100Ωm - 500Ωm are silts, 500Ωm - 1500Ωm are fine-grained sands, 1500Ωm - 3000Ωm are medium-grained sands, 3000Ωm - 5500Ωm are coarse-grained sands, and > 5500Ωm as sandstone.

By using a depth of 1.2m and a minimum of 750Ωm in the evaluation; the vicinity of VES 8 is the most suitable site for the construction of high rising building. This is followed by VES station 9, 6, 14 and 15. While the unsuitable sites for the construction of high rising building are VES 4, 10, 11, 12 and 16 (Fig. 13).

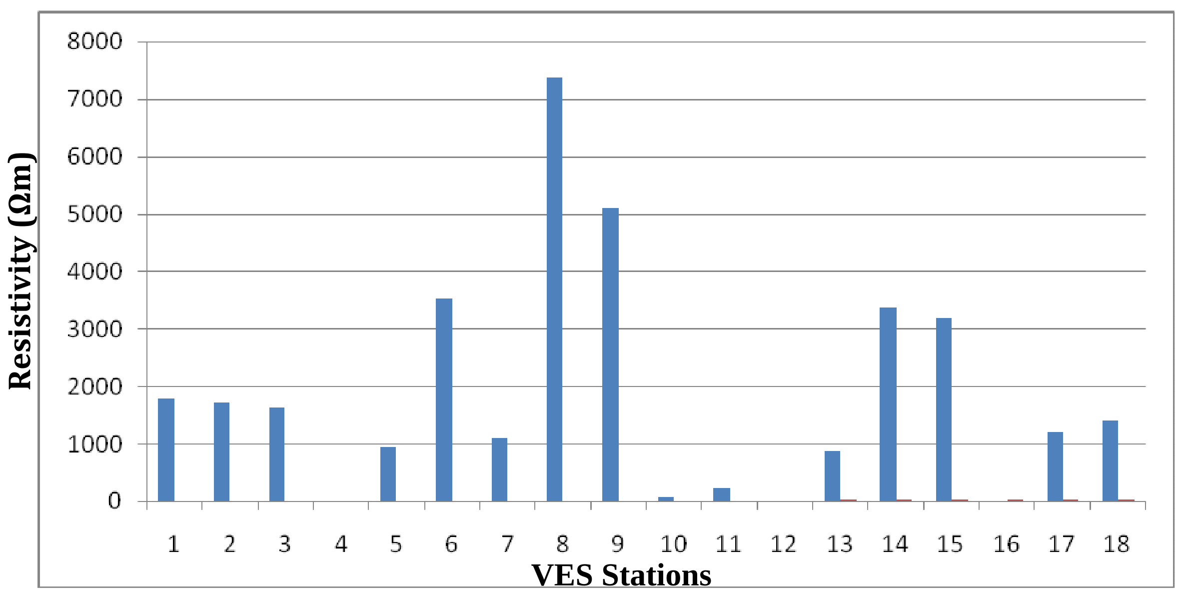

Fig. 13: A histogram of the foundation competence of the subsurface based on resistivity values of the study area

Recall that the higher the value of a layer resistivity, the higher the competence; therefore the lower the value, the lesser the competence. From the resistivity values of topsoils, the vicinity of VES 3, 4, 7, 16 and 17 are poor materials for any structural engineering purpose (Fig. 14). This is evident from the usual cracking and collapse of the portion of road along Umuahia-Ikot-Ekpene highway where the data of VES 17 was acquired. This could be associated with the outcrop of local clay lenses at the vicinity.

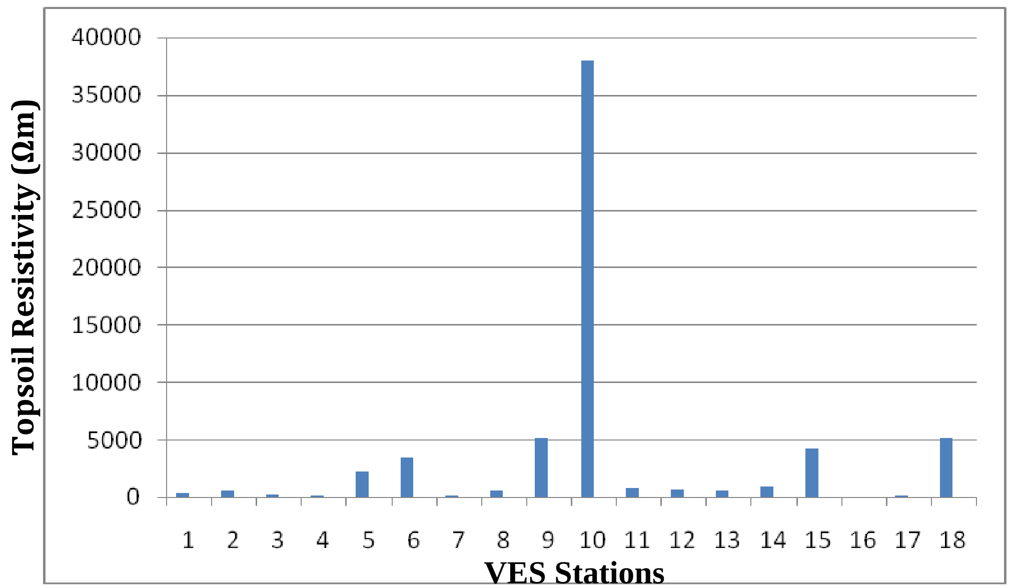

Fig. 14: A histogram of Topsoil resistivity of the study area

CONCLUSIONS

The geophysical results revealed three to six geoelectric sequences within the study area which comprises topsoil, sands, silts, clays and possibly gravel. The thickness of the topsoils range from about 0.2m to about 5.0m; but most are less than 2m. The thickness of the topsoils of the vicinity of VES 6, 9, and 14 are by far greater than 2m probably because construction work have been done in the area and the topsoils must have been removed during the levelling of the area for the construction.

By using the resistivity values together with depth of 1.2m in the evaluation, the vicinity of VES 8, 9, 6, 14 and 15 are suitable for the construction of high rising building; while the unsuitable sites are VES 4, 10, 11, 12 and 16. Also, the vicinity of VES 1, 2, 3, 5, 7, 13, 17 and 18 can be considered for such construction under the supervision of structural and geotechnical experts.

Further foundation investigation using alternative detailed geophysical (seismic) and geotechnical investigations of the area is also recommended.

REFERENCES

AASHO (1962). “Road Test – Report 5 (Pavement Research)”, Highway Research Board, Special Report 6IE Washington D.C.

AASHTO (1988). Manual on subsurface investigations American Association of State Highways and Transportation Officials Washington D.C.

Adeleke, B. O. and Goh Cheng Leong, (1978). Certificate Physical and Human Geography, West African Ed. Oxford University Press, Nigeria, Ibadan.

Ajayi, O., Olorunfemi, M.O., Ojo, J.S., Adegoke, C.W., Chikwendu, K.K., Oladapo, M.I., Idornigie, A.I., Akinluyi, F., (2005). Integrated geophysical and geotechnical investigation of a dam site on River Mayo Ini, Adamawa State, Northern Nigeria. Afr. Geosci. Rev., 12(3): 179-188.

Akinrinmade A.O (2013). Geophysical and geotechnical investigation of river Ero for dam site, Ajuba, south-western Nigeria. Msc. Thesis submitted to the Department of Geology,University Of Ilorin, Kwara State, Nigeria. 114pages.

Akintorinwa, O. J. and Adeusi F. A. (2009). Integration of Geophysical and Geotechnical Investigations for a Proposed Lecture Room Complex at the Federal University of Technology, Akure, SW, Nigeria. Journal of Applied Sciences 2(3), 2009

Amajor, L.C. (1986). Alluvial fan Facies in the Miocene-Pliocene Coastal Plain Sands, Niger Delta, Nigeria. Journal of Sedimentary Geol. Vol. 49; p. 1-20.

Amos-Uhegbu, C., Igboekwe, M.U., Chukwu, G.U., Okengwu, K.O. and Eke, K.T. (2012). Hydrogeophysical Delineation and Hydrogeochemical Characterization of the Aquifer Systems in Umuahia-South Area, Southern Nigeria. British Journal of Applied Science & Technology, 2(4): 406-432.

Amos-Uhegbu, C., Igboekwe, M.U., Chukwu, G.U., Okengwu, K.O. and Eke, K.T. (2014). Geo-electrical Delineation and Geochemical Characteristics of Aquifer Systems in Kwa-Ibo River Watershed, Abia State, Nigeria. Journal of Scientific Research & Reports 3(6): 818-843.

Asseez, L.O. (1976). Review of the stratigraphy, sedimentation and structure of the Niger Delta. In: Kogbe, C.A. (ed.). Geology of Nigeria. Elizabeth Publ. Co.: Lagos, Nigeria, 259–272.

Bayewu, O. O., Oloruntola, M. O., Mosuro, G. O. and Abass, O. K. (2012). Preliminary Investigation of a Proposed Dam Site along River Ome, Ago Iwoye South Western Nigeria. Journal of Science and Technology Volume 1 No. 6.

Bowles, J.A., 1990. Engineering Properties of Soil and their measurements. McGraw Hill, NewPort carrol, D.1970. claymmerah. A guide to their X-ray identification.Geol Soc Am. Spec.pap 80 Pp.

Brink, A. B. A., Parridge, J. C. and Williams, A. A. B (1992). Soil Survey for Engineering, Claredon, Oxford.

Chukwu, G.U. (2010). Electrical resistivity survey to investigate causes of borehole failure within Ikwuano/Umuahia area of Abia State, SE Nigeria. PhD Dissertation, Michael Okpara University of Agriculture, Umudike, Nigeria. 104pages.

Fatoba J.O, Alo J.O and Fakeye A.A. (2010). Geoelectric Imaging for Foundation Failure Investigation at Olabisi Onabanjo University (O.O.U) Minicampus, Ago Iwoye, Southwestern Nigeria. Journal of Applied Sciences Research, 6(12): 2192-2198, 2010**.**

Federal Ministry of Works and Housing (1972). Highway Manual Part 1 Road Design, Federal Ministry of Works and Housing, Lagos.

Geological Survey of Nigeria 'GSN' (1985): Geological Map of Nigeria. Federal Ministry of Mines and Power, Lagos.

Hunter, L.E., Powers, M.H. and Rose, R.S. (2011). Geophysical evaluation of earthen dam foundations, US army corps of engineers, ISC, p33

Jones, A.A and Hockey, R.A. (1964). The geology of part of southern Nigeria. Geology Survey. Nigeria. Bull.1964; 31.10p.

Kogbe, C.A. (1976). Paleogeographic History of Nigeria from Albian Times In: Kogbe C.A. (ed) African Geology. Elizabethan Pub. Co. Lagos 436p.

Mbonu P.D.C, Ebeniro J.O, Ofoegbu C.O. and Ekine A.S. (1991). "Geoelectric sounding for the determination of aquifer characteristics in parts of the Umuahia area of Nigeria," Geophysics, 56: 284–291.

Melikan, R.E. (1960). Geophysical Activity Applied to Engineering Construction and Groundwater Project. *Geophysics.*, 33: 9-11.

Møller, I., and Sørensen, K. I. (1998). A new approach for fast 2-D geoelectric mapping of near surface structures: European Journal of Environmental and Engineering Geophysics 2, 247–262.

Murat, R.C. (1972). "Stratigraphy and Palaeogeography of the Cretaceous and Lower Tertiary in southern Nigeria". In: Dessauvagie, T.F. J. and Whiteman, A. (eds.). African Geology. UI Press: Ibadan, Nigeria. pp 635 – 641.

Neil, A. and Ahmed, I. (2006). A generalized protocol for selecting appropriate geophysical techniques. Dept of Geol. and Geophys. University of Missouri-Rolla. Rolla, Missouri.2006; 19p.

NHBC, (2011) National House-Building Council, UK. Technical guidance note and Building Amendment Regulation.

Obaje, N. G. (2009). Geology and Mineral Resources of Nigeria, *Lecture Notes in Earth Science,* Springer-Verlag, Berlin.

Olorunfemi, M.O and Meshida, E.A. (1987). Engineering Geophysics and Its Application in Engineering Site Investigation (case study of Ile-Ife area. *The Nigeria Engineer., 22(2): 57-66.*

Olorunfemi, M.O., Idoniege, A.I., Coker, A.T. and Babadiya, G.E. (2004). The Application of the Electrical Resistivity Method in Foundation Failure Investigation, a Case Study of O.A.U Dental Clinic. Global Journal of Geophysical Science, 2004, 2(1): 139-151.

Olorunfemi, M.O., Ojo, J.S., Sonuga, F., Ajayi, O. and Oladapo, M.I. (2000). Geoelectrical and Electromagnetic Investigation of the Failed Koza and Nasarawa Earth Dams Around Katsina, Northern Nigeria. J. Mining Geol., 36(1): 51 - 65.

Oluwakemi, A.O. and Michael, L.O. (2011). Geoelectric investigation of Owuruwuru Dam site, Ikere Ekiti, Southwestern Nigeria. Journal of Geology and Mining Research. Vol. 3.pp.12.

Oluyide, P.O. (1988). Structural Trends in the Nigerian Basement Complex. In Precambrian Geology of Nigeria. Geological Survey of Nigeria: pp. 93–98.

Onyeagocha, A.C. (1980). Petrography and Depositional Environment of the Benin Formation, Nig. J. Min. Geol; 17 (2): 147-151.

Orellana, E. and Mooney, H.M. (1966). Master Tables and Curves for Vertical Electrical Sounding over Layered Structures. Interciencia, Madrid, pp 34

Oyawoye, M.O. (1972). The Basement Complex of Nigeria. In: Dessauvagie, T.F.J; Whiteman A.J (eds), *African Geology*. University Press, Ibadan, Nigeria. 67-69.

Reyment, R. A. (1965). Aspects of the geology of Nigeria: Ibadan University Press

Sheriff, R. E. (2001).*Encyclopedic Dictionary of Applied Geophysics.* University of Houston. 422pages.

Short, K.C. and Stauble, A.J. (1967). Outline of Geology of Niger Delta. AAPG Bull. 51: 761-

769.

Sowers, G.B. and Sowe, G.F. (1970). Introductory soil mechanics. 3rd edition. 556 pages. Macmillan (New York)

Society of Exploration Geophysicists (1990). "Resistivity and induced polarization methods," Geotechnical and Environmental Geophysics Volume I Review and Tutorial. S. H. Ward, ed., Tulsa, OK, pp 147-190.

Stoneley, R. (1966). The Niger delta region in the light of the theory of continental drift: geol. Mag., vol 105, p385-397.

Susan, E. P. (2006). The role of geophysics in 3-D mapping. Geological Survey of Canada. 2006; ON, KIA 0E8.

Tabwassah, C.A and Obiefuna, L.O. (2012). Geophysical and Geotechnical Investigation of Cham Failed Dam Project, Nigeria. Research Journal of Recent Sciences Vol. 1(2).

Vander -Velpen, B.P.A. (1988). "RESIST version 1.0". A Resistivity depth sounding interpretation software. M.Sc. Research Project. ITC: Netherlands.

Zohdy, A. A. R. (1989). A New Method for the Automatic Interpretation of Schlumberger and Wenner Sounding Curves.*Geophysics*, 54(2): 245-253.