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Subsoil Characterization for Foundation Stability Using Geophysical and Geotechnical Methods

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Abstract
An Integrated geophysical and geotechnical subsoil characterization of parts of the new stadium complex, Akure, southwestern Nigeria had been carried out with a view to characterize the subsoil materials for stability of proposed engineering foundation. Five (5) magnetic and three (3) dipole-dipole profiling were carried out at station separation of 10 m along the traverses. Twenty one (21) Vertical Electrical Sounding (VES) measurements were made at selected locations along the traverses. A total of five (5) soil samples were collected from a dug pit at a depth of 1.0 m for laboratory analysis. The magnetic profiles delineated characteristic one to two negative peak amplitude anomalies that are typical of thin dipping dyke models (suspected to be fractures, shear zones, faults or geological contacts) along Traverses 1-5. The 2-D geomagnetic section delineated overburden thicknesses ranging from 5 – 15 m along the Traverses. The subsurface geologic units delineated by the geoelectric sections and the 2-D resistivity images consisting of the topsoil, weathered layer, partly weathered/fractured basement and fresh bedrock. Part of the topsoil and the weathered layer are characterized by low resistivity values suggestive of the presence of clay and or weak geomaterials at a depth range of 1 – 4 m within which civil engineering foundation are usually placed. These zones and the fractured/fault zones delineated by the magnetic methods constitute weak geomaterials that are considered to be inimical to civil engineering structures within the study area. Results of geotechnical analysis of soil samples adjudged plasticity indices of samples A, C and D to be of high index and were characterized by high plasticity/compressibility and consequently of low engineering competence. Samples B and E were classified as low-medium plasticity/compressibility, and are rated moderate–high engineering competence. However, it was observed that soil with higher liquid limits or plasticity index have lower electrical resistivity values and hence were adjudged low in engineering foundation competence. Based on the analysis of the results obtained from this study, the engineering foundation suitability of the soil were generally classified as good (B and E), fair (D) and poor (A and C). It can therefore be concluded that the subsoil in the investigated area are generally of low to high civil engineering competence.
Keywords: Geophysical; Geotechnical; Subsoil; Competence; Characterization; Foundation, Stability.
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1. Introduction

In recent time, the statistics of failures of civil engineering infrastructures such as roads, buildings, bridges and dams in Nigeria has increased geometrically (Coker, 2015). Building collapse has been experienced in both Basement Complex and Sedimentary areas within the country. Field observation show that in March, 2019, Nigeria experienced two building collapse within three days, one at Ita-Faji, Lagos Island and the other one at Idi-Arere, Ibadan. Following this 149 building were marked for demolition in Lagos Island by the Lagos State Physical Planning Department.

Other reported building collapse in the country includes: Elu Ohafia in Ohafia Local Government Area, Abia State (The Nation News, 11th July, 2019); Jos, North Local Government Area, Plateau State, (16th July, 2019); Agwana street, Abraka and Asaba both in Deta State, (20th July, 2019); 48 Arisha water front Otun Araromi street, Magodo phase 1 Lagos, (12th October, 2019); Lagos Community Mosque at Olowora bus stop in Ikosi-Isheri, Lagos state, (13th October, 2019), (LASEMA, 2019); Butcher Street, Terminus Market in Jos, North Local Government Area, Plateau State, (16th July, 2019). All the reported building collapse above involved loss of lives and many are injured with consequential economic loss which covered both Basement Complex and sedimentary terrains of Nigeria.

Since building collapse has crept quietly into the Nigeria horizon in the early 1990's. It has now become an unabated major treat to life and huge means of economic waste. Poor supervision of projects, poor construction materials, poor engineering design are probable reasons speculated to have been responsible for this ugly incidence by the engineering community. Unfortunately, one major factor that has always not been given serious attention in this part of the world is lack of adequate information on the nature of subsurface geologic conditions prior to construction exercise. However, since every engineering structure is seated on geo-materials, it is imperative to conduct pre-construction geological, geophysical and geotechnical investigations of such site.

Engineering structures are designed and constructed with long life expectancy (Olorunfemi, 2000). Apart from loss of huge financial investment, other consequences of structural failure can be devastating, including loss of lives and properties. All the civil engineering structures erected on the earth have their own substructures (foundation). A reliable foundation design depends on the characteristics of both the geological structures and the near subsurface soil or rock. Therefore, the nature (i.e. competence, strength and load bearing capacity) of the soil supporting the super structure becomes an extremely important issue of safety, structural integrity and durability of the super structure. Hence, a detail investigation of the subsoil is required by non-destructive techniques such as geophysical methods which respond to the heterogeneous nature of soil particles through some physical parameters that govern the subsoil competency.

The choice of the geophysical method is usually determined by the geologic set up and the existence of significant contrast in the physical properties of the subsurface layers. (Ako and Adepelumi, 2006). Geophysical and geotechnical methods have enjoyed integrated approach to complement each other in engineering site investigation for better assessment of geo-materials. Geotechnical investigation of geo-materials takes longer time, discrete, invasive, more expensive and can impact on the environment while geophysical surveys have proven useful as a rapid means of obtaining subsurface information on a continuous profiling basis, it is non-invasive and cost-effective over large areas. Several authors have singly engaged geophysical approach or integrated geophysical and geotechnical methods in site investigation (Akintorinwa and Adesoji, 2009, Osinowo, 2011, Akinrimade *et al*., 2013, Folahan, *et al*., 2013, Oladunjoye, *et al*., 2014, Adejumo *et al.*, 2015, Coker, 2015 and Adedoyin, 2017).

In engineering and foundation studies, geophysics plays a significant role in the investigation of subsurface material and geological structures which are likely to have significant engineering implications. Therefore, the essence of this work is the need to characterize the subsoil using combined geophysical and geotechnical methods to ascertain the engineering competence of the geo-materials beneath the study area.

2. Site Location and Description.

The site under investigation is the proposed 40,000 seats capacity Ondo State new stadium, located in Araromi area, Akure, Southwestern Nigeria (Fig. 1). The site is located along Ilesa-Akure-Owo Road. It is situated between the geographic coordinates of Easting's 741704 and 742704 mE and Northings of 804011 and 805438 mN in the Universal Transverse Mercator (UTM) scale Mina zone 34 (Fig. 1). The site occupies an area extent of about 1.4 km^2. The study area is accessible through the Akure-Owo Road and Onyearugbulem Market-Oja Oba road Akure (Fig. 1).

3. Geology and Engineering Competence

The study area is underlain by the Precambrian Basement Complex Rocks of southwester Nigeria (Rahaman, 1976). Field observation show that the lithologic unit identified in the study area includes the migmatite gneiss, granite gneiss and granite (Fig. 2). The rock unit outcrops in few places within the study area. It is expected that near surface fresh basement rock are highly competent as subgrade material for engineering foundation but when subjected to weathering and structural deformation arising from previous tectonics, it may not be able to satisfy its initial expected load bearing capacity. Therefore, basement rocks which have experienced weathering and featuring are likely to have implication on the expected engineering infrastructure sited on it.

4. Methodology

Five Traverses, 200 m apart and about 250 m long, oriented in the E-W directions were established in the study area. Stations were established at 10 m apart along each of the Traverses. The geophysical methods involved the magnetic profiling and electrical resistivity methods. The geoelectric method adopted the Vertical Electrical Sounding (VES) and combined horizontal profiling/Vertical Electrical Sounding (VES)/2-D imaging techniques were used in this study (Fig. 1).

4.1 Magnetic Survey

Ground magnetic survey was carried out with the Proton Precession Magnetometer along five traverses (Fig. 1). A base station was first established with the co-ordinates taken and ten (10) readings were taken at the base station. Total field measurements were taken at regular intervals of 10 m along the traverses with two readings taken at each station and then averaged. This is done in order to be able to calculate the diurnal variation for the area of study with respect to the time the readings were taken. Ten (10) final readings were taken at the base station after the survey was completed along the traverses. After taken measurements along each traverse, the base station measurements were repeated. The raw field magnetic data were corrected for diurnal variation and offset by subtracting the base station regional magnetic reading from the reading recorded along the traverse line at corresponding time. The magnetic data were interpreted quantitatively using the 2-D Euler Deconvolution software. The interpretation results are presented as profiles and map.

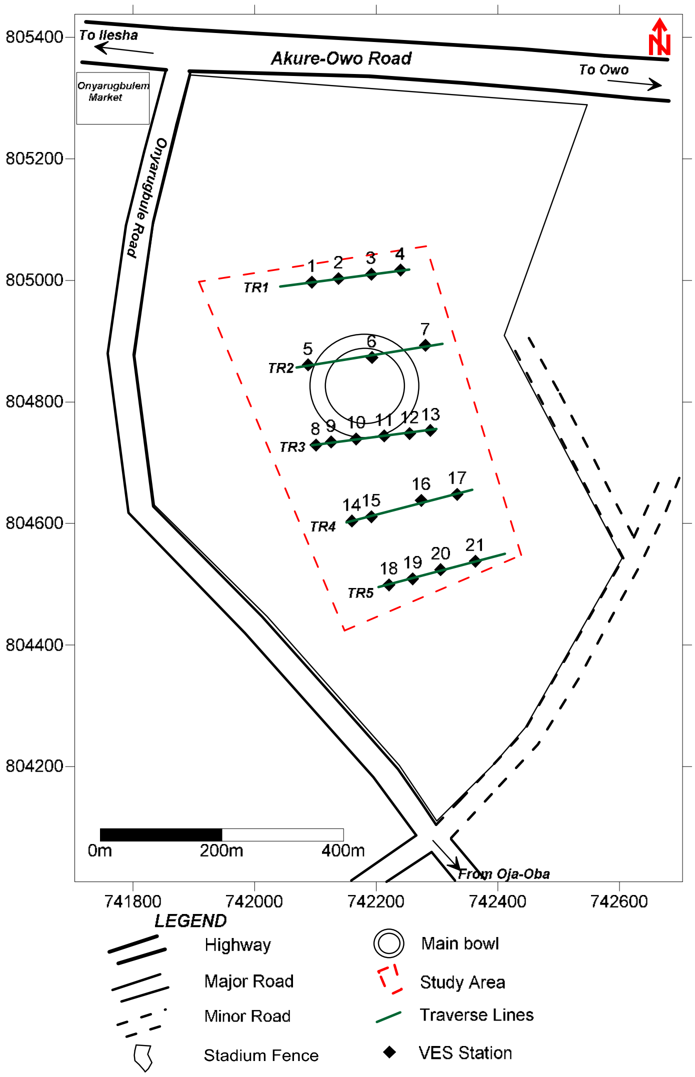


Fig. 1: Location and Data Acquisition Map of the Study Area

4.2 Electrical Resistivity Survey

4.2.1 The Vertical Electrical Sounding (VES)

A total of twenty one (21) Vertical Electrical Soundings (VES) were conducted along the five traverses within the study area using Ohmega resistivity meter (Fig. 1). Schlumberger array was employed with the minimum half current electrode spread (AB/2) varied from 1 to a maximum of 225 m. The VES data were interpreted using the Partial curve matching technique quantitatively to obtain the initial geoelectric parameters (layers' resistivities and thicknesses). The initial geoelectric parameters obtained were fed into the computer as a starting modeling parameters using Win RESIST version 1.0 (Vander Velpen, 2004). The VES interpretation results (layers' resistivities and thicknesses) were used to develop the geoelectric sections and maps.

4.2.2 Combined Horizontal Profiling/Vertical Electrical Sounding (VES)

The combined Horizontal Profiling/Vertical Electrical Sounding technique was carried out using Dipole – Dipole array along Traverses 1, 3 and 5 (Fig. 1). This was done to delineate the subsurface geologic structures and to map the continuous vertical and horizontal variation of resistivity within the subsurface. The inter-electrode spacing *a* of 5 m was adopted. While inter-dipole separation factor (n) was varied from 1 to 5. The apparent resistivity values obtained were plotted at the intersection of two lines drawn at 45° from the mid points of the potential and current dipole. The 2-D inversion modelling of the dipole-dipole data was carried out using DIPPRO™ software. This gave the 2-D resistivity structure of the subsurface geologic units. The results of the magnetic and the 2-D resistivity structures were used to select Vertical Electrical Sounding (VES) positions along the Traverses. Three to six VES were conducted along each of the traverse lines for the subsurface correlation.

4.2.3 Geotechnical Soil Sampling

Soil sampling location were established and distributed to cover the perimeter and other important part of the proposed building foundation within the investigated site. (Fig. 1). A total of five (5) disturbed soil samples were collected from a test dug pits at a depth of 1.0 m. The samples were collected in a polythene sac, labelled for

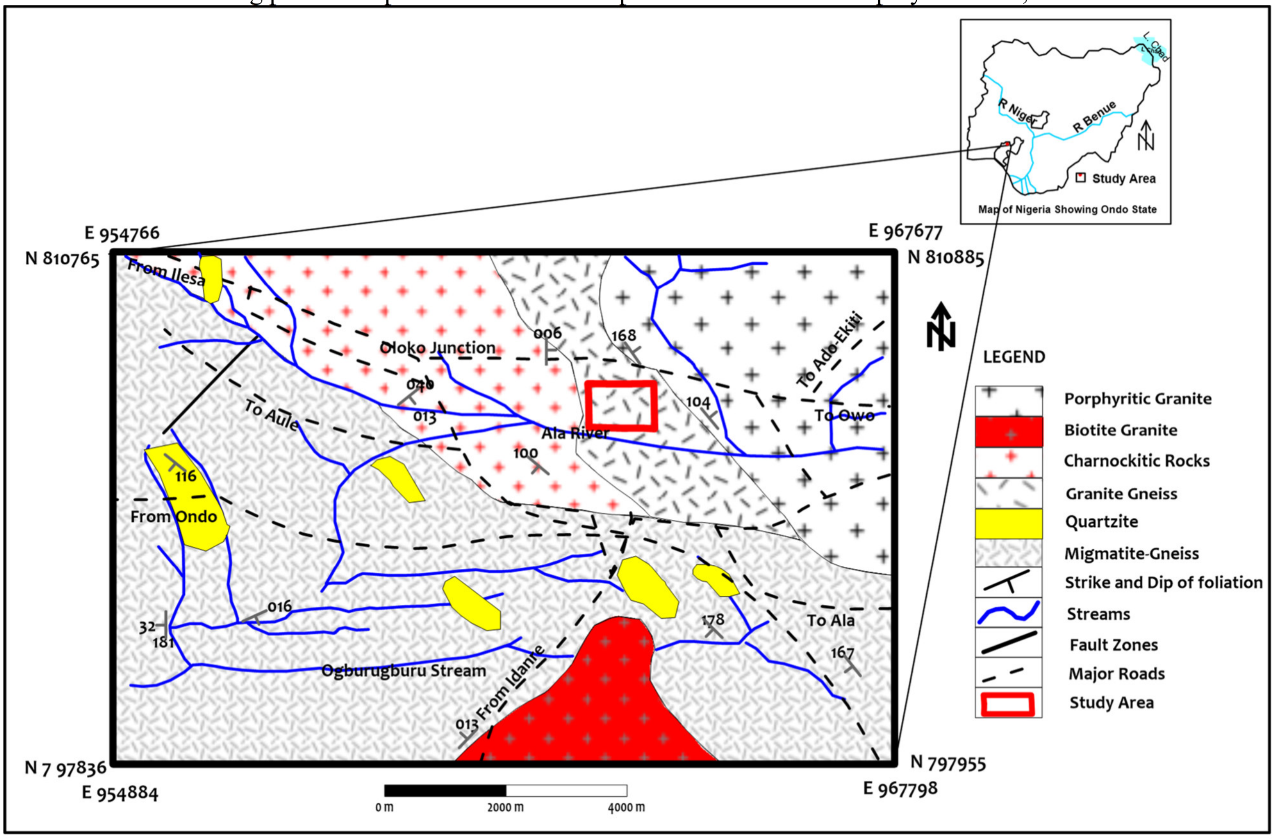


Fig 2: Geological Map of Akure Showing the Study Area (Modified After Owoyemi, 1996)

proper identification and taken to the laboratory for geotechnical analysis. The data were analyzed for; natural moisture content, grain size analysis, Atterberg limit, linear shrinkage, and strength properties such as consolidation and Unconfined Compressive Strength test. The tests were conducted in accordance with B. S. 1377 (BSI, 1990).

5. Results and Discussions

5.1 Magnetic Profiles

The residual total field magnetic profiles and the corresponding 2-D Euler deconvolution generated geomagnetic sections along traverses 1–5 are shown in (Figs. 3 (a and b) – 7 (a and b)). The amplitude of the magnetic field generally varies from -450 nT to 600 nT within the investigated area (Fig. 3 (a and b) – 7 (a and b)). Only one major magnetic anomaly with characteristic negative peak amplitude was observed along traverse 1 (Fig. 3a and b) while one or two anomalies with negative peak amplitudes were identified along traverses 2–5 (Figs. 4 (a and b) – 7 (a and b)). These anomalies are typical of thick/thin dipping dyke models (suspected to be fractures, shear zone, faults or geological boundaries) (Parasnis, 1986). The anomalies were identified between distances 0 – 180 m; 0 – 90 m and 100 – 200 m; 0 – 150 m and 150 – 190 m; 30 – 180 m; and 0 – 80 m and 80 – 190 m respectively along traverses 1 – 5.

The 2-D geomagnetic sections delineated overburden thickness of materials lying above the basement along the five magnetic profiles to vary from 5 – 15 m (Figs. 3 b – 7 b). The geomagnetic sections show that the basement topography in the investigated area is gently undulating. A summary of the quantitative interpretation results of the magnetic anomalies are presented in Table 1.

5.2 Geomagnetic Map

The distribution of the residual total field magnetic data obtained within the study area was contoured to produce the geomagnetic map (Fig. 8). The map reveals regions of both magnetic lows and highs whose magnetic field intensity ranges between -450 nT and 950 nT. Characteristic magnetic lows of -450 to -50 nT in the northeast and southeastern part of the investigated area is suspected to be indicative of low magnetic signatures that are suspected to be geologic structures (fractures, faults and shear zones).

5.3 Electrical Resistivity Method

5.3.1 Depth Sounding Curves

Table 2 shows the summary of the interpreted results of the twenty one (21) VES curve obtained from the study area. The curve types obtained in the study area are the A, H, K, KH, HA, AKH, HKH and KHKH. The pie chart

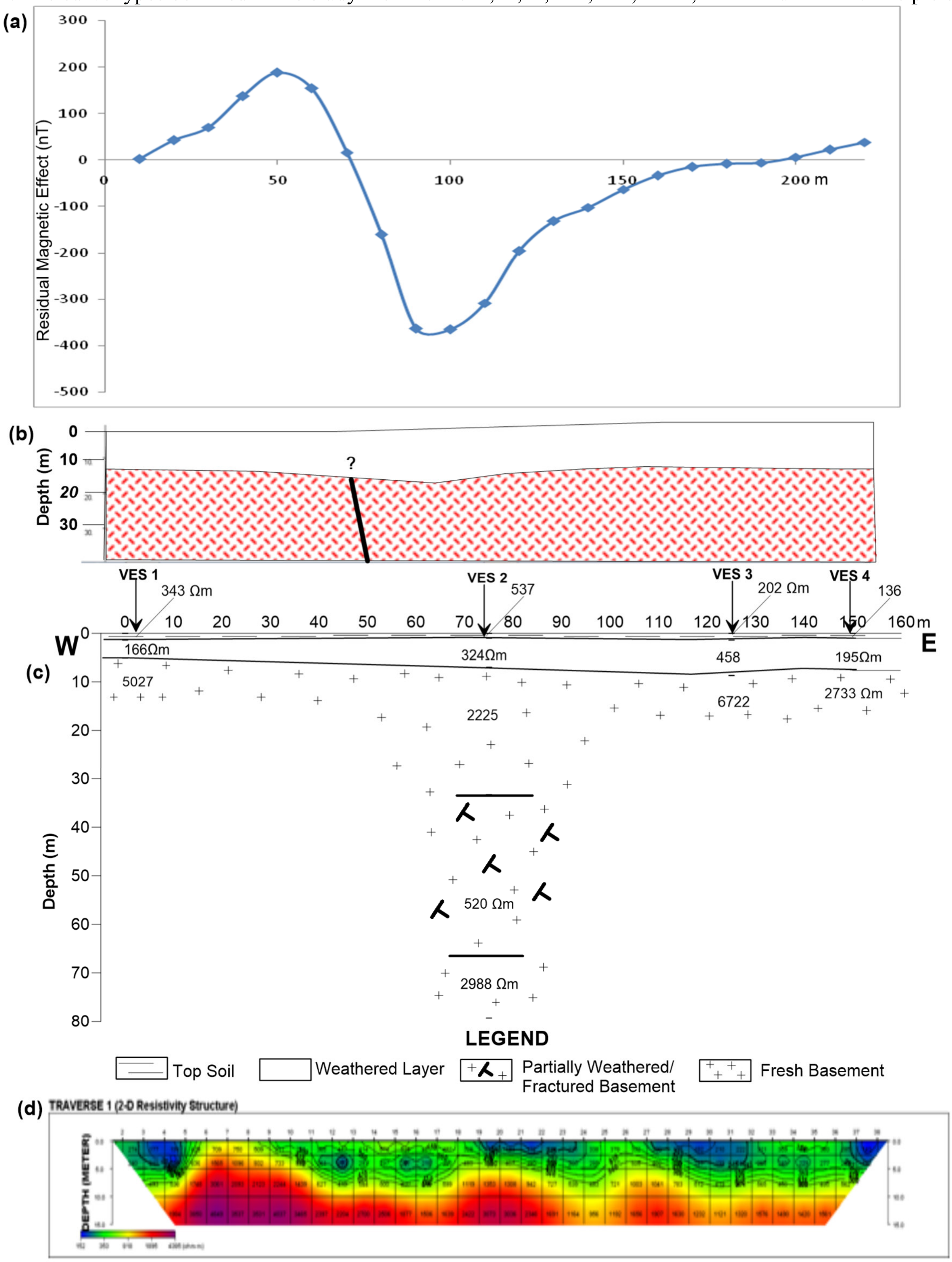


Fig. 3: Correlation of (a) Magnetic Profile, (b) Geomagnetic Section (c) Geoelectric Section and (d) Dipole-dipole Pseudosection along Traverse 1

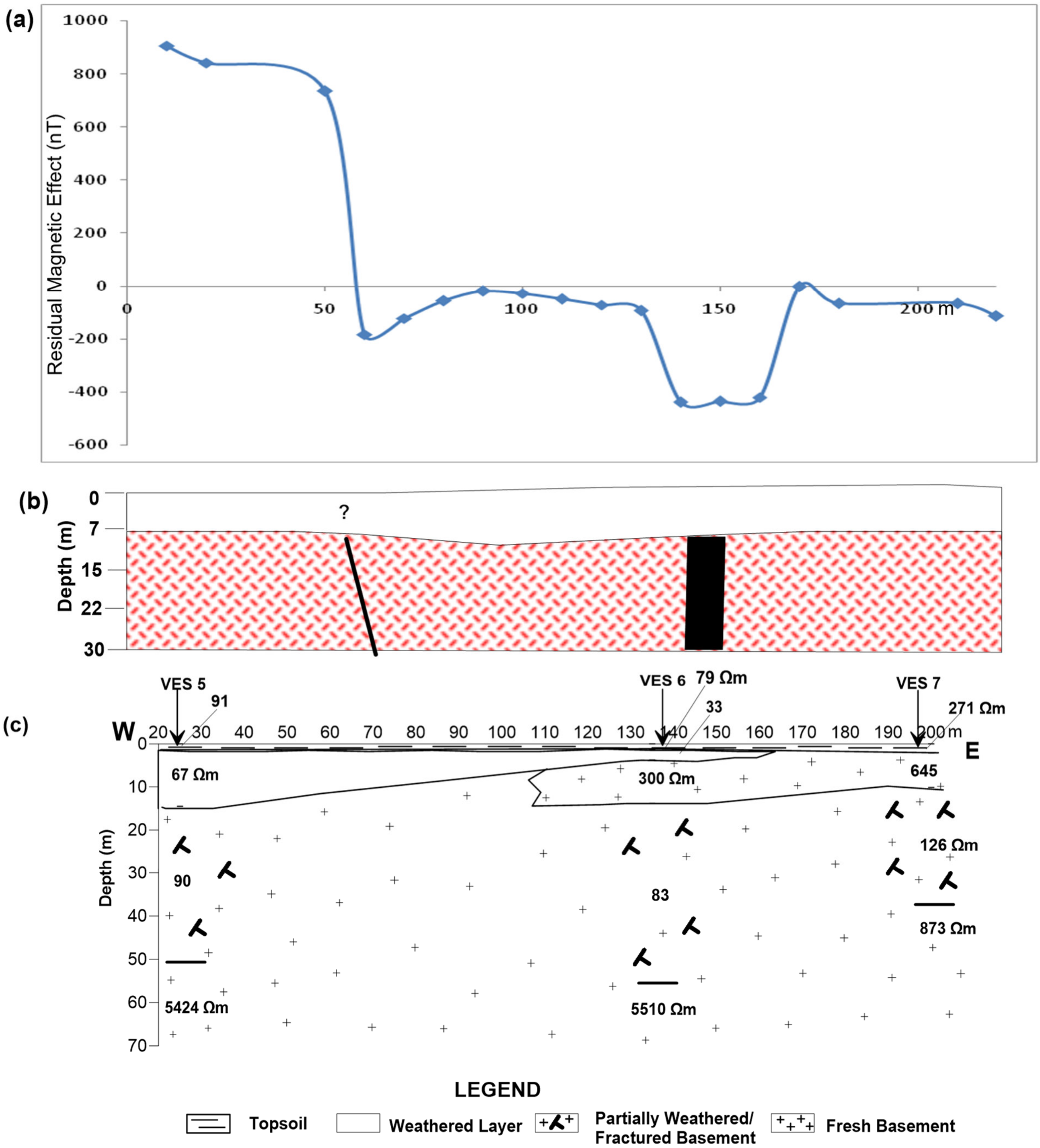


Fig. 4: Correlation of (a) Magnetic Profile, (b) Geomagnetic Section (c) Geoelectric Section along Traverse 2

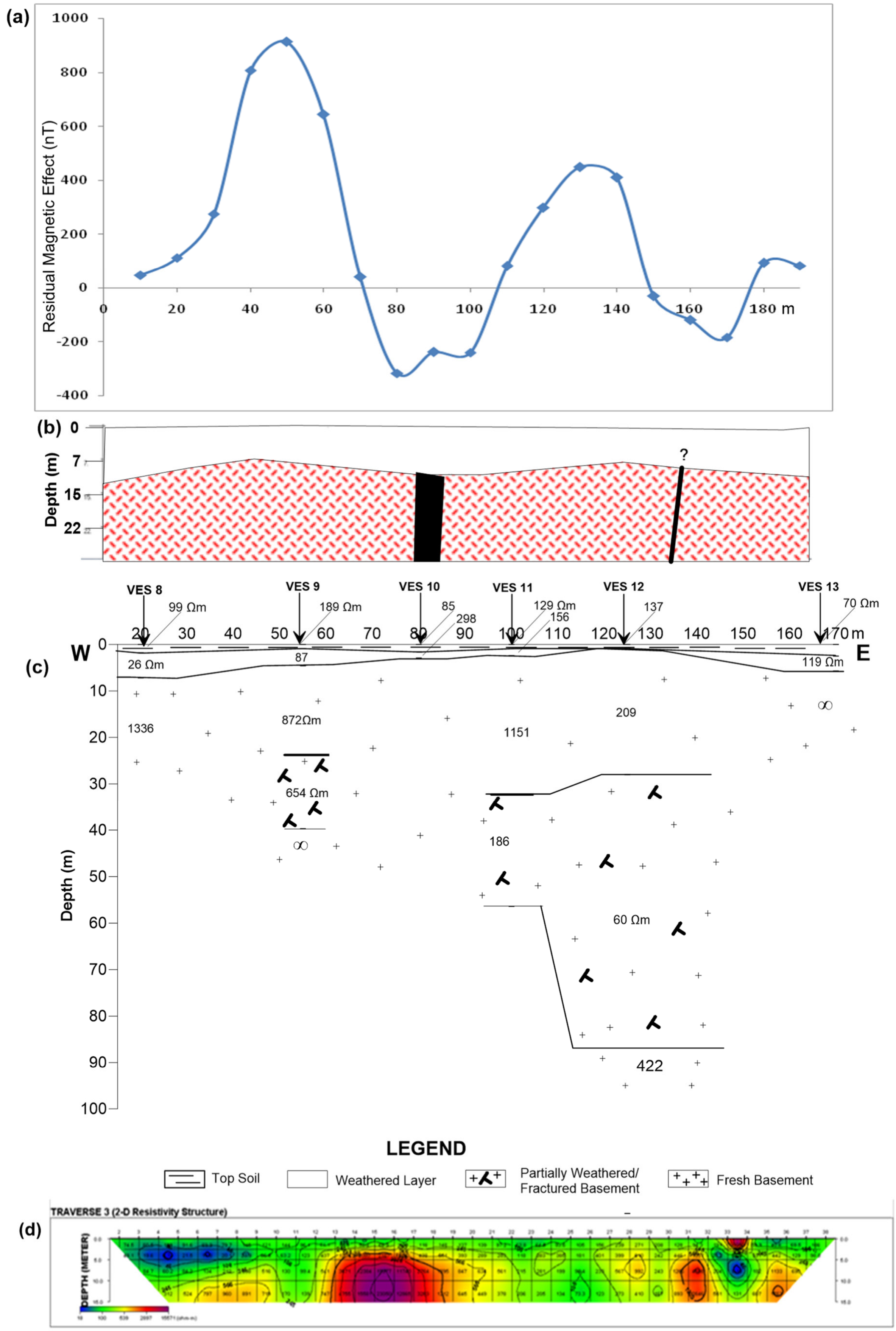


Fig. 5: Correlation of (a) Magnetic Profile, (b) Geomagnetic Section (c) Geoelectric Section and (d) Dipole-dipole Pseudosection along Traverse 3

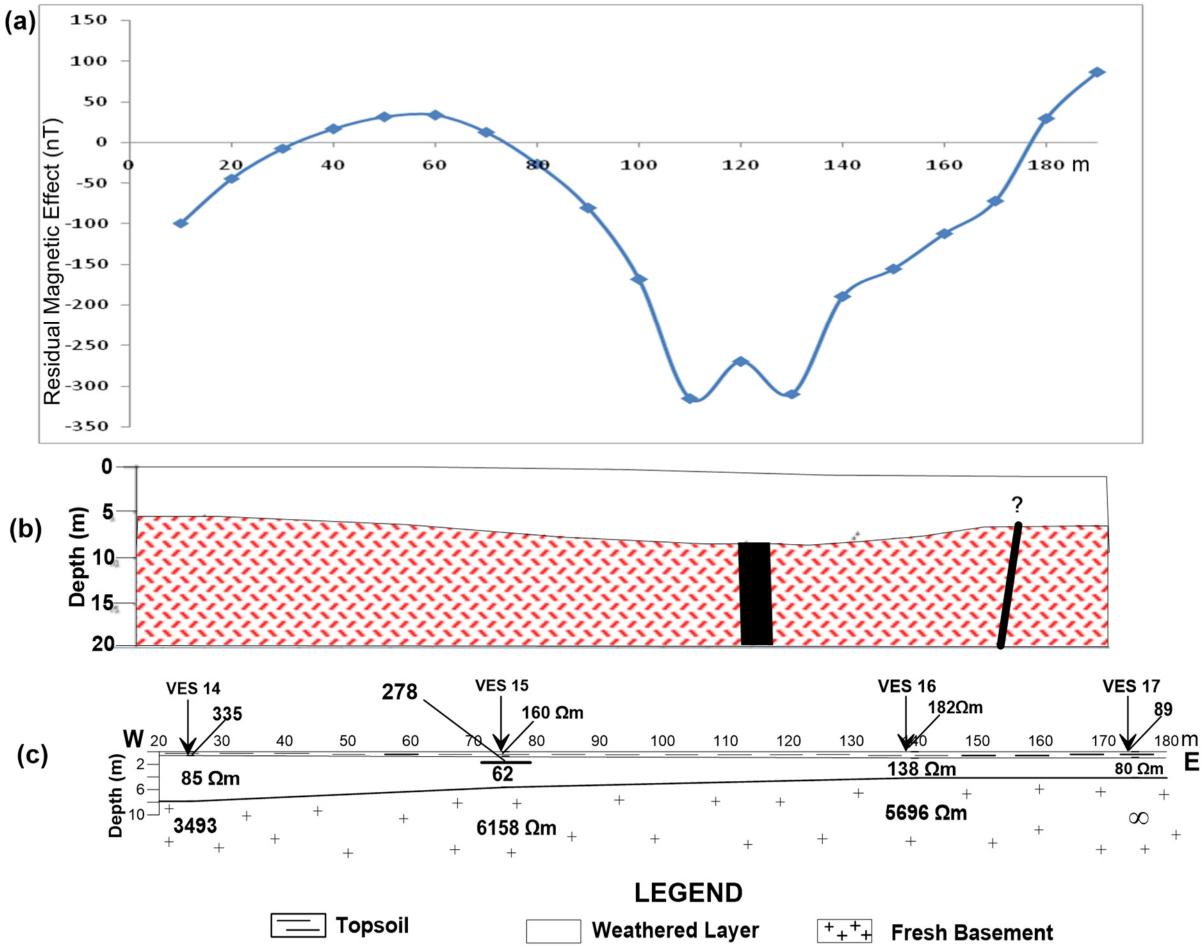


Fig. 6: Correlation of (a) Magnetic Profile, (b) Geomagnetic Section (c) Geoelectric Section along Traverse 4.

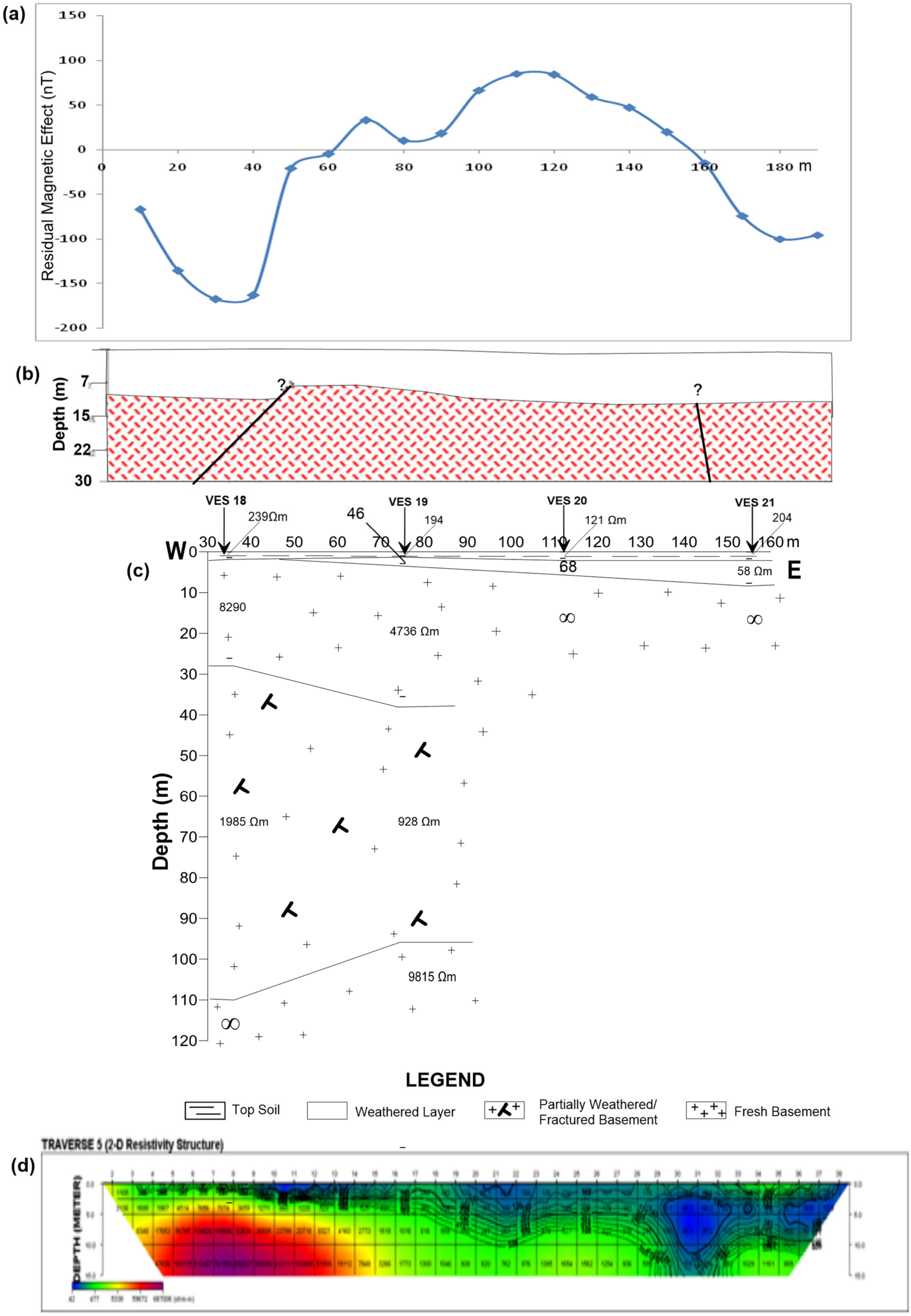


Fig. 7: Correlation of (a) Magnetic Profile, (b) Geomagnetic Section (c) Geoelectric Section and (d) Dipole- dipole Pseudosection along Traverse 5

Table 1: Summary of the Interpretation Results of the Magnetic Anomalies.

Traverse No.	Magnetic Anomaly Width (m)	Location of Top of Magnetic Basement (m)	Estimated Depth to Magnetic Basement (m)
1	180	110	14
2	90 and 100	60 and 150	7 and 10
3	150 and 40	90 and 165	9 and 7
4	150	130	7
5	80 and 110	50 and 158	7 and 12

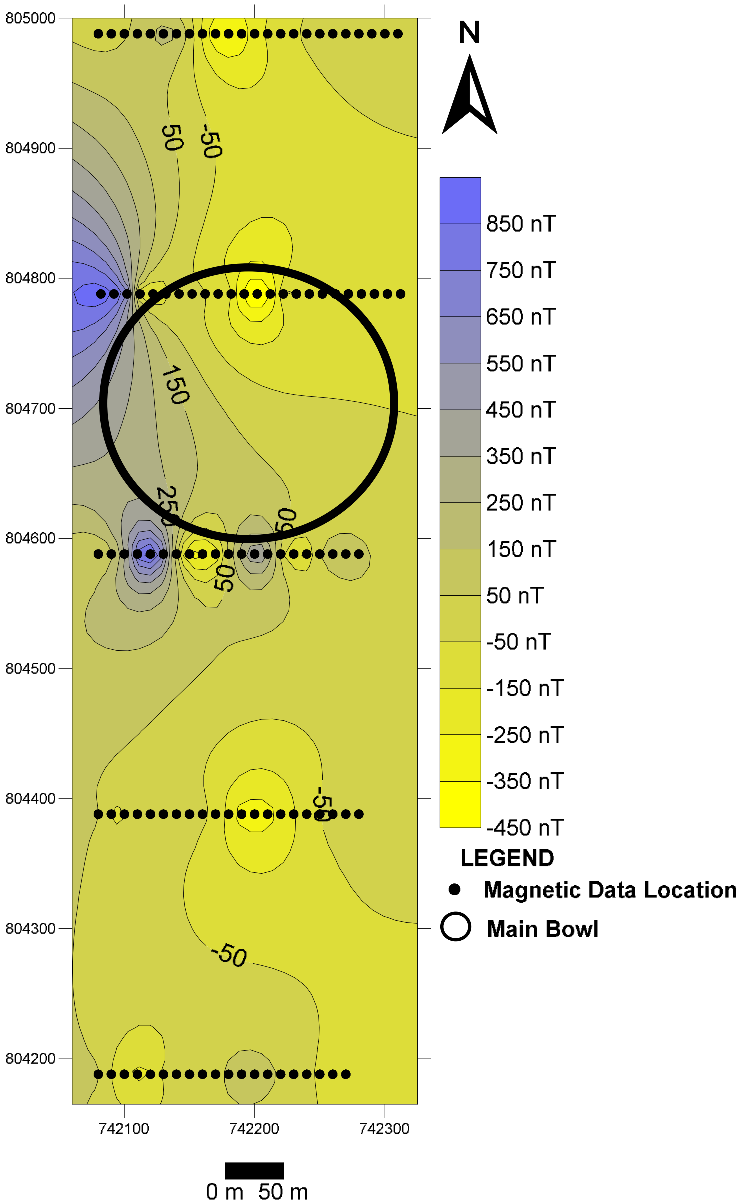


Fig. 8: Geomagnetic Map of the Study Area.

in (Fig. 9) shows the percentage frequency distribution of the curve types within the investigated area. The predominant curve type in the study area is the H-curve type having a percentage frequency of 43% while A type has 24%. The other curve types are K, HA and AKH-curves types with each represented by 5% distribution while HKH and KH curve types are also represented equally by 9% (Fig. 9). Figure 10 shows the typical depth sounding curves type obtained from the study area. The predominance of the H curve type implies that the topsoil which usually range from < 0.5 – 2.5 m within which engineering foundation are usually placed are characterized by higher resistivity values than the underlying layer. The near surface (topsoil) high resistivity values observed is indicative of high competence for engineering foundation.

Table 2: Summary of Interpretation Results of VES

VES S/No	Layers	Resistivity Value Ωm)	Thickness (m)	Lithological Characteristics	Curve Type
1	3	343 166 5027	1.4 4.7 -	Topsoil Weathered Layer Fresh Basement	H
2	5	537 324 2225 520 2988	1.0 6.0 26.3 46.0 -	Topsoil Weathered Layer Fresh Basement Partly weathered/Fractured Basement Fresh Basement	HKH
3	3	202 458 6722	1.4 7.3 -	Topsoil Weathered Layer Fresh Basement	A
4	3	136 195 2733	1.0 6.5 -	Topsoil Weathered Layer Fresh Basement	A
5	4	90 66 90 ∞	1.4 13.0 36.1 -	Topsoil Weathered Layer Partly Weathered/Fractured Basement Fresh Basement	HA
6	5	79 33 300 83 5510	1.3 2.4 10.2 32.5 -	Topsoil Weathered Layer Fresh Basement Partly weathered/Fractured Basement Fresh Basement	HKH
7	4	271 645 126 873	2.1 8.1 27.3 -	Topsoil Fresh Basement Partly Weathered/Fractured Basement Fresh Basement	KH
8	3	99 26 1336	1.8 5.4	Topsoil Weathered Layer Fresh Basement	H
9	3	179 87 ∞	0.9 3.6 -	Topsoil Weathered Layer Fresh Basement	H
10	3	85 298 2400	1.6 1.3 -	Topsoil Weathered Layer Fresh Basement	A
11	5	129 156 1151 187 ∞	0.9 1.5 30.0 24.0 -	Topsoil Weathered Layer Fresh Basement Partly weathered/Fractured Basement Fresh Basement	AKH
12	3	137 209 60 4218	0.8 27.2 56.5 -	Topsoil Weathered Layer Partly weathered/Fractured Basement Fresh Basement	K
13	3	70 119 ∞	2.5 3.2 -	Topsoil Weathered Layer Fresh Basement	A

14	3	335 85 3493	0.6 7.2 -	Topsoil Weathered Layer Fresh Basement	H
15	4	160 278 62 6158	0.7 1.0 3.9 -	Topsoil Weathered Layer Weathered Layer Fresh Basement	KH
16	3	182 138 5696	0.9 3.2 -	Topsoil Weathered Layer Fresh Basement	H
17	3	89 80 ∞	1.4 2.4 -	Topsoil Weathered Layer Fresh Basement	H
18	3	239 8290 1965 ∞	1.7 24.7 72.6 -	Topsoil Fresh Basement Partly weathered/Fractured Basement Fresh Basement	A
19	3	194 1146 4736 928 ∞	1.0 1.9 32.6 60 -	Topsoil Weathered Layer Fresh Basement Partly weathered/Fractured Basement Fresh Basement	H
20	3	121 68 ∞	1.6 3.1 -	Topsoil Weathered Layer Fresh Basement	H
21	3	200 33 ∞	2.0 3.3 -	Topsoil Weathered Layer Fresh Basement	H

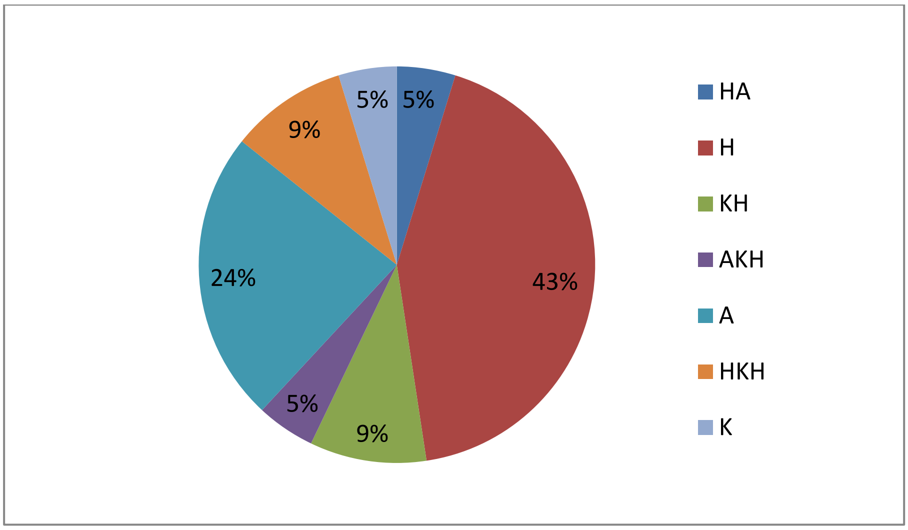
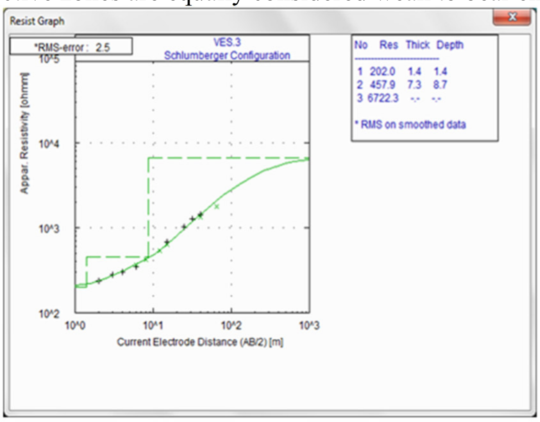


Fig. 9: Pie Chart Showing Percentage Frequency Distribution of Curve Types in the Study Area.

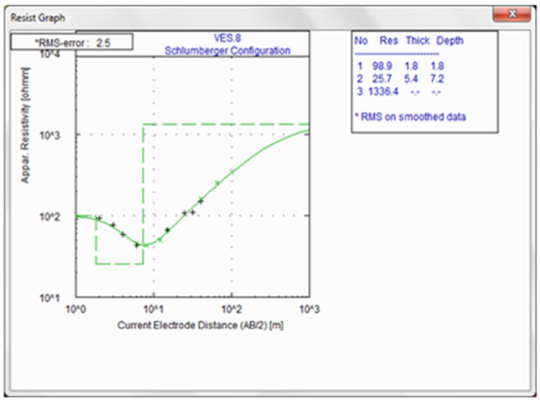
5.3.2 2-D Resistivity Structure

The 2-D resistivity structures obtained along traverses 1, 3 and 5 from the investigated area are shown in (Figs. 3 (iii) – 7 (iii)). The 2-D resistivity structures identify four subsurface layers. These are the topsoil, weathered layer, partly weathered/fractured basement and the fresh basement. The topsoil is submerged in the equally low resistivity weathered layer. The topsoil is characterised with very low resistivity values of 7 – 22 ohm-m in deep blue and greenish colour bands between stations 1– 6, (14 – 23 m), 19 – 25 (95 – 117 m), 27 – 32 (135 – 160 m) and 36 – 38 (183 – 193 m) along traverse 1 (Fig. 3 (iii); 3 – 8 (15 – 39 m) along traverse 3 (Fig. 5 (iii); and 3 – 38 (15 – 190 m) along traverse 5 (Fig. 7 (iii). The topsoil within the identified zones above are considered to be highly conductive (clayey materials) and hence are identified as weak and unstable zones. There is need for caution in siting engineering foundation in such areas.

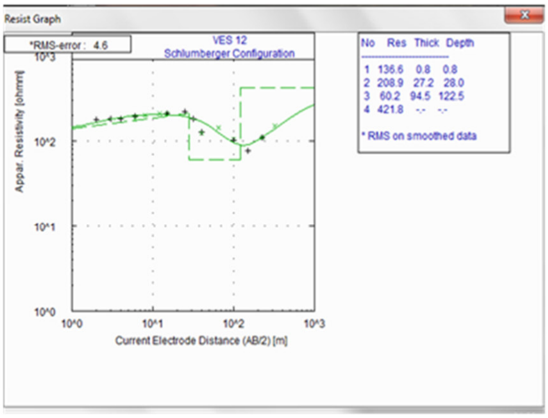
The second layer is the weathered layer. It is characterised by deep blue to greenish colour bands. The resistivity values generally range from 7 – 250 ohm-m. The thickness vary from about 2.5 – >15 m in many places. The patches of very low resistivity zones (< 50 ohm-m) (in deep blue colour bands) found within the low resistivity weathered layer within the zones outlined in the description of the topsoil are characterized by conductive zones (clay soil, peat or abandoned land fill/dumpsites). The conductive zones varies from 2.5 – >15 m between stations 3 – 6 (15 – 30 m), 10 – 24 (50 – 120 m), 27 – 32 (135 – 160 m) and 36 – 38 (180 – 190 m) along traverse 1; 3 – 9 (15 – 45 m) and 32 – 35 (160 – 175 m) along traverse 3; and 10 – 38 (50 – 190 m) along traverse 5. These conductive zones are equally considered weak to bear enginnering structure.



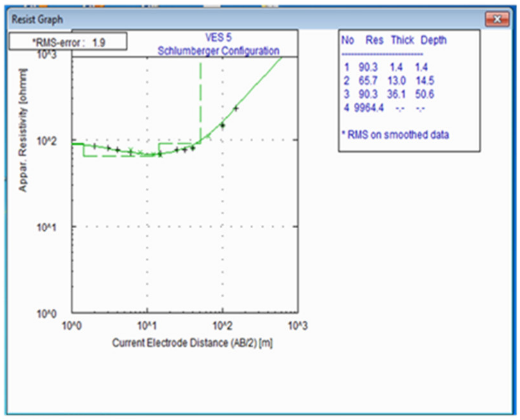
(a) A- Curve Type



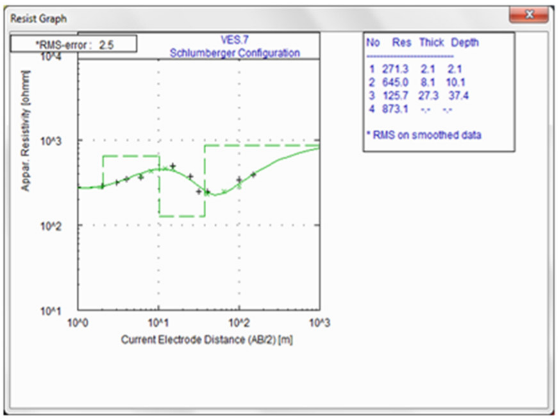
(b) H-Curve Type



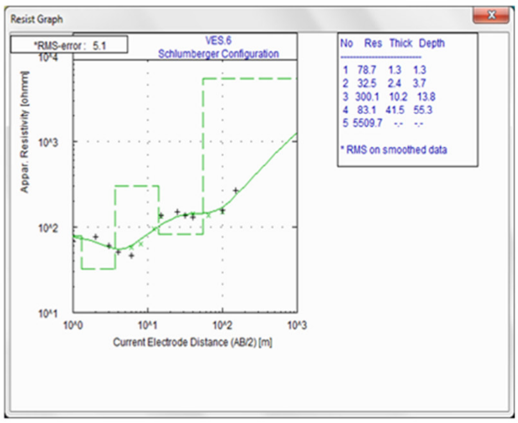
(c) K-Curve Type



(d) HA-Curve Type



(e) KH-Curve Type



(f) HKH-Curve Type

Fig. 10 (a-f): Typical Depth Sounding Curves Obtained in the Study Area

The third layer is the fractured basement. The fractured basement is characterized by low resistivity found between two basement bedrocks (Figs. 3 (iii) and 5 (iii)}. The fractured zones are characterized by bluish to greenish colour bands. The resistivity range from 6.5 – 500 ohm-m between stations 10 –12.5 (50 – 62.5 m), 21 – 30 (105 – 150 m) and 32 – 35 (110 – 125 m) along traverse 3. The thickness varies from 3.5 – >15 m in these places. The fractured zones are mainly confined at relatively deeper depth of 15.9 – 133.6 m as observed from the

2-D resistivity structure, may pose little or no threat to engineering foundation in the study area.

The last layer is the fresh basement bedrock. The resistivity is characterised by moderately high to very high resistivity values of up to 2007 ohm-m (yellowish to red colour bands). Depths to the basement bedrock vary from about <1 to >15 m. The basement topography is gently undulating (Figs. 3 (iii), 5 (iii) and 7 (iii)). These deductions are corroborated by the geoelectric sections and the geomagnetic sections.

5.3.3 Geoelectric Sections

The VES interpretation results were used to generate geoelectric sections. The summary of the interpreted geoelectric parameters obtained in the study area are presented in Table 3. The geoelectric sections delineate five subsurface geologic layers (Table 3). These are the topsoil, weathered layer, fresh basement, fractured basement and fresh basement bedrock (Figs. 3d – 7d).

Table 3: Summary of Geoelectric Characterization of the VES Interpretation Results.

Layering	Resistivity Range (ohm-m)	Thickness (m)	Lithologic Description
Topsoil	70 – 537	0.6 – 2.5	Clay, Sandy clay, Clayey sand and Lateritic.
Weathered layer	33 – 458	1.3 – 13.0	Clay/Sandy Clay, Clayey sand and Lateritic.
Basemen rock	209 – 8290	8.1 – 32.6	Fresh basement
Fractured basement	60 – 1985	15.9 – 72.6	Partly weathered and Fractured basement rock.
Basement Bedrock	422 – ∞	–	Fresh basement.

***Depth to Bedrock varies from 2.1 to 13 m**

5.4 Correlation of Geophysical Results

The correlation of the Magnetic, dipole-dipole 2-D resistivity structure profiles and the geoelectric sections are presented in (Figs. 3 (a-d) - 7 (a-d)). Typical thick/thin dipping dyke suspected to be fractures, shear zones, faults or geological boundaries were observed along the magnetic profiles and the 2-D geomagnetic sections (Figs. 3 (a-e) - 7 (a-e))}. This anomalies were identified between distances 0 – 180 m along traverse 1; between distances 0 – 90 m and 100 – 200 m along traverse 2; between distances 0 – 150 m and 150 – 190 m along traverse 3; between distances 30 – 180 m along traverse 4; and between distances 0 – 80 m and 80 – 190 along traverse 5. The geoelectric section delineated partly weathered/fractured zones beneath some VES along Traverses 1, 2, 3, and 5. However, the 2-D resistivity structure did not delineate any subsurface structure along Traverse 1.

The identified conductive zones with moderately high conductivity/low resistivity zones (conductive soils) which occur at relatively shallow depth are classified as weak zones within the subsurface geology which are suspected to be inimical to the location of civil engineering infrastructures within the investigated area. However, these results show that there is a good correlation from the results of all the geophysical methods used in this study.

5.5 Resistivity Maps

Figure 11a shows the distribution of the resistivities of the topsoil within the study area which generally range from 70 – 540 Ωm (Fig. 10a). It is observed that the area within the main bowl of the stadium is characterized by moderately low resistivity values of 70 – 150 Ωm suggesting clay/sandy clay, topsoil and by implication, it is considered to be moderately geotechnically competent for sitting of some of the proposed structures in the stadium. However, the northern and southern parts of the main bowl are dominated by relatively high resistivity values of 180 – 540 Ωm, indicating sandy clay, clayey sand, and lateritic material at shallow depth. Generally, the topsoil in the area can be inferred to be relatively more stable and competent enough to host civil engineering foundation. The weathered layer resistivity map (Fig. 11b) show resistivity values which generally rage from 21- 645 Ωm with dominant resistivity values of > 100 Ωm characterizing major part of the study area, including the main bowl of the stadium which indicates moderate – high resistive (competent geo-material) whose composition are sandy clay, clayey sand and laterite are considered competent for engineering structures. However, pockets of low resistivity zones exist within the main bowl, western and southeastern part of the study area. These areas that are characterized by relatively low resistivity values (<50 Ωm) are composed of clay, and are considered to be geotechnically incompetent for the proposed structure (Fig. 11b). The bearing capacity of this layer may need to be considered while designing foundation for building in the identified area.

5.5.1 Isopach Maps

Figure 12a display the isopach map of the topsoil which shows the distribution of the topsoil thickness in the study area. The topsoil thickness range from 0.6 – 2.4 m which revealed that the topsoil is generally thin (0.6 – 1.6 m) in the north, central and southern part of the investigated area. The north eastern, southeastern and a small area in the eastern part of the investigated area have thickness which range from 1.8 – 2.1 m in the study area.

The isopach of map of the weathered layer is shown in (Fig. 12b). It generally range from 1.3 – 13 m. The weathered layer thickness is thin 1.0 – 7.0 m is observed in the northern, eastern, western and southern parts of the study area. However, weathered layer thickness with higher value of 8.0 – 13.0 m is found in northwestern part close to the main bowl of the stadium. The large variation in the weathered layer thickness along Traverse 2 implies uneven basement topography. When an engineering structure is placed to straddle between thin 2.0 – 4.0 m and thick > 4.0 – 13.0 m thick weathered layer, this can initiate strain in the building foundation and may initialise failure and its eventual collapse.

5.5.2 Bedrock Topography Map

The bedrock relief map of the study area is presented in (Fig. 13a). The map reveals gentle undulation in the relief of the subsurface basement. The major part of the investigated area located in the north, central, eastern flank and the southern part of the study area are characterized by thin (1 – 7 m) overburden materials. This is supported by the thin overburden thickness observed from geomagnetic sections, 2-D resistivity structures and the geoelectric sections generated for the study area. These areas are considered to be relatively stable for sitting engineering structures.

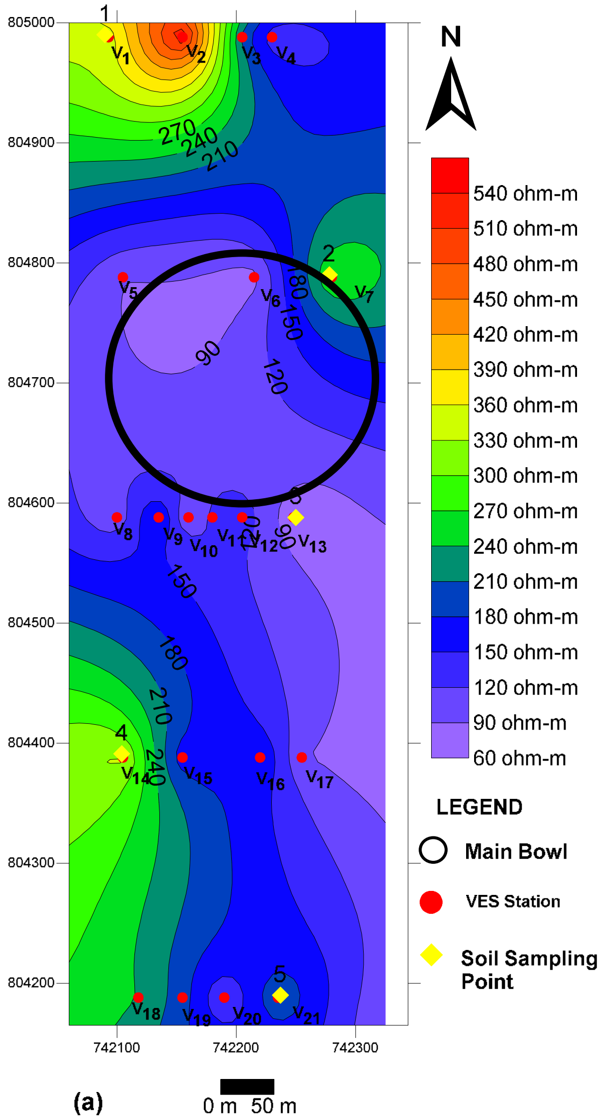
5.5.3 Structural Map of the Study Area

The structural map of the study area developeded from the magnetic profiles is presented in (Fig. 13b). The map show two major subsurface structural dicontinuities within the basement bedrock designated F1 and F2 is delineated in the investigated area. This discontinuity is suspected to be a major fault/fracture zone in the study area. The fault/fracture zones are observed to cut across the study area in a north – south direction. This suggests that extreme care is needed by engineers working at the site in designing and location of engineering foudation in the study area.

5.5.4 Subsoil Characterization of the Study Area

The subsurface geoelectric units delineated beneath the investigated area include the topsoil, weathered layer, partly weathered/fractured basement and the fresh basement bedrock. The topsoil constitutes the layer within which normal civil engineering foundation is founded at a depth range of 1-4 m. This layer is made up of clay, sandy clay and clayey sand Table 4.

Fig. 11a shows the topsoil resistivity distribution map of the study area. The topsoil resistivity map shows that the study area is underlain by resistivity values which range from 62-537 ohm-m. The topsoil resistivity values were used for the rating of subsoil competence of the investigated area based on Idornigie *et al.*, (2006). The rating of the subsoil competence of the study area using resistivity values is presented in Table 4. It is observed that the area within the main bowl of the study area is characterized with moderately low resistivity values of 70 – 150 Ωm suggesting sandy clay, topsoil and by implication, it is considered to be moderately geotechnically competent for siting of some of the proposed structures in the stadium (Table 4). The peripheral of this low resistivity zone occupying the central part is bordered and extends to the southern and northern parts by a moderately higher resistivity values which range from 100-350 ohm-m. This zone is composed of sandy clay and hence, rated to be moderately competent (Table 4). A small portion in the northwestern part of the investigated area is underlain by subsoil characterized by resistivity values which fall in the range of 350-750 ohm-m. This range of resistivity values is composed of clayey sand/laterite. It is rated to be competent for civil engineering structure (Table 4). To avoid future catastrophy, extreme care is required in the are characterized by low resistivity zones by civil enginers designing building foundation at the site.



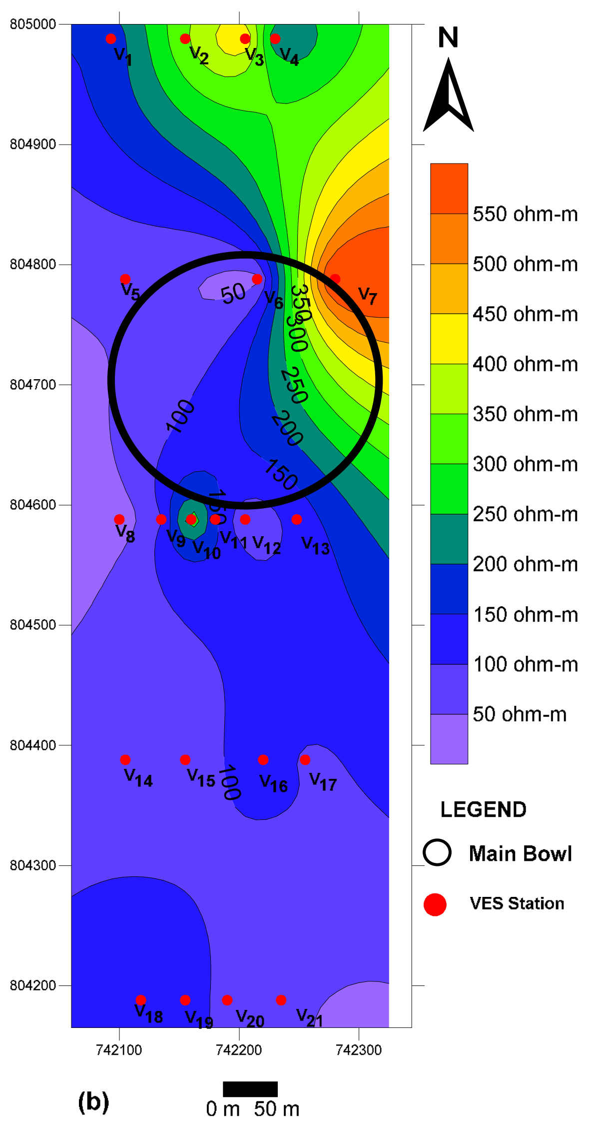


Fig. 11: (a) Topsoil Resistivity and (b) Weathered layer Resistivity Maps in the Study Area.

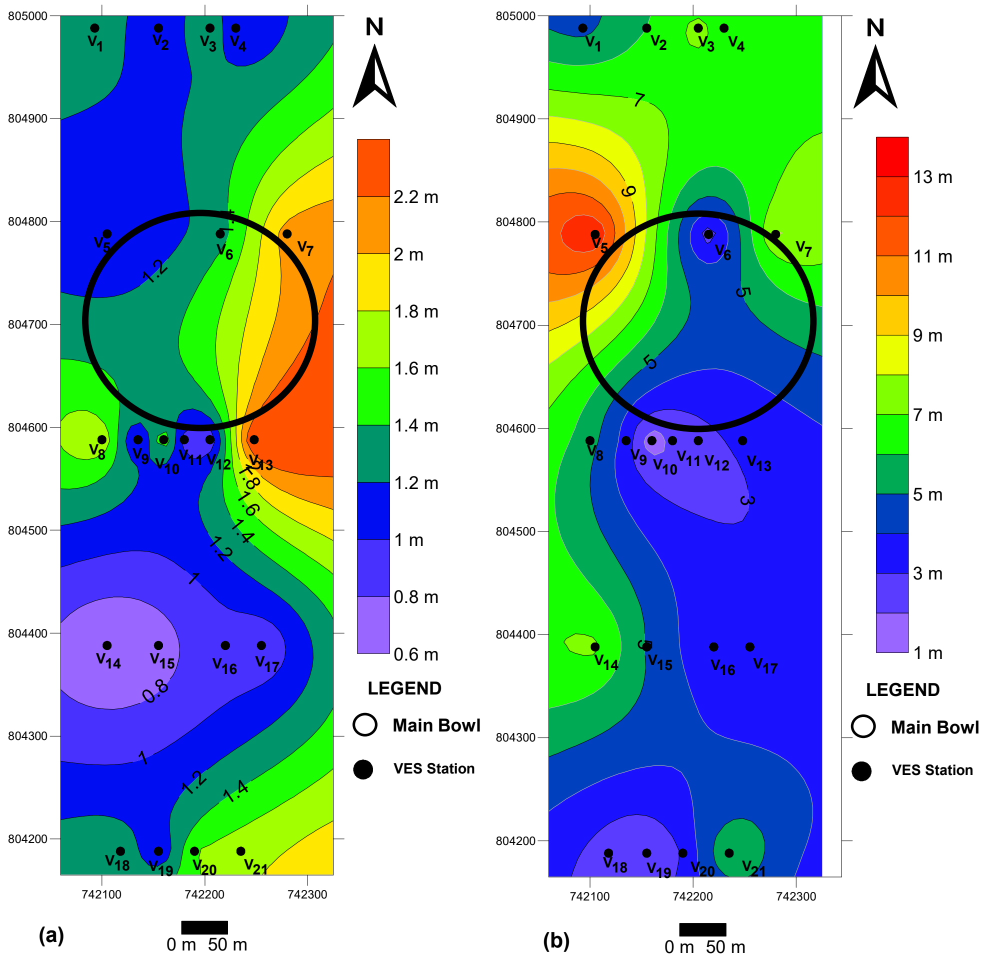


Fig. 12: (a) Topsoil Thickness, (b) weathered Layer Thicness Maps in the Study Area

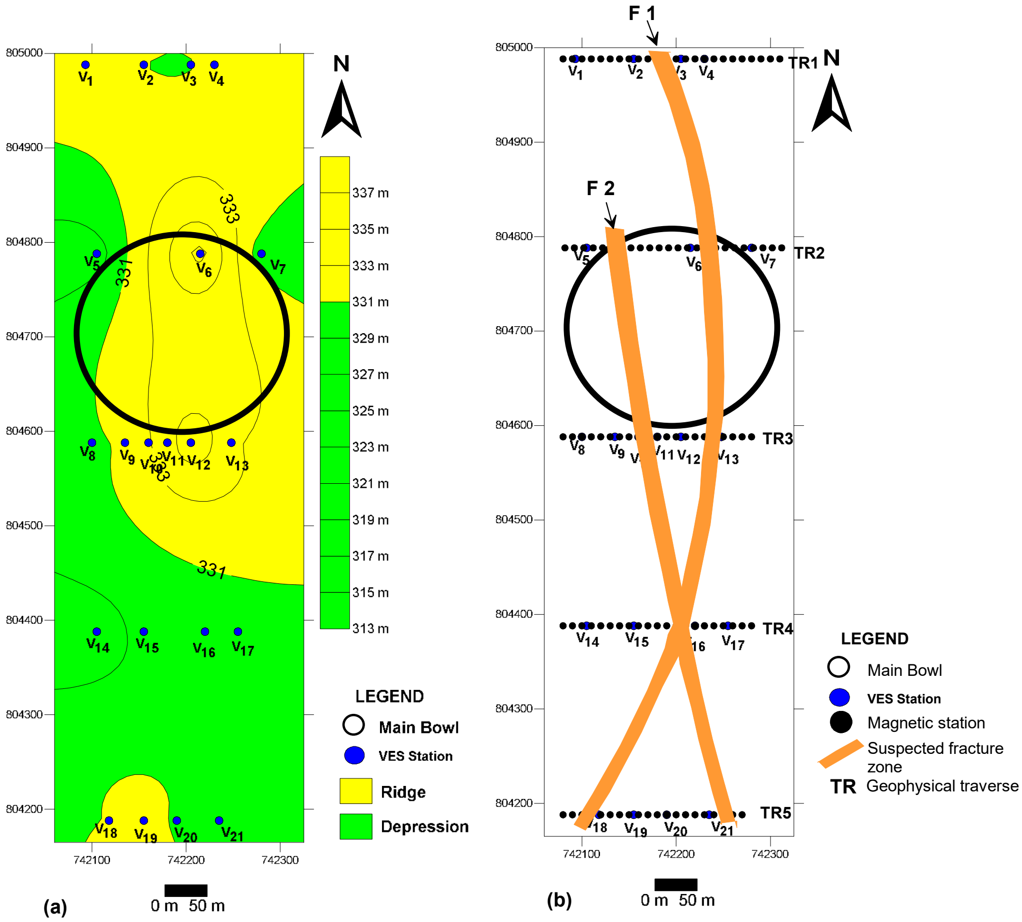


Fig. 13: (a) Bedrock Releif Map, (b) Magnetic Structural Map of the Study Area.

Table 4: Rating of Subsoil Competence of the Topsoil in the Study Area using Resistivity Values.

Layering	Resistivity Range (ohm-m)	Thickness (m)	Lithologic Description	Competence Rating	Soil Sample
Topsoil	≤ 100 100-350 350-750	0.8-1.8 0.6-2.1 1.0	Clay Sandy clay Clayey sand	Incompetent Moderately competent Competent	C and D B and E A

5.6 Geotechnical Results

Table 5 shows a summary of the geotechnical classification of the subsoil in the study area using plasticity index based on Adeyemi and Oyediran, (2004). It is observed from Table 5 that samples B and E are characterized by low-medium index classification and are characterized by low-medium plasticity/low-medium compressibility and high-moderate civil engineering competence respectively. Samples A, C and D have high index classification and are characterized by high plasticity/high compressibility and consequently, low engineering competence Tables 4 and 5 further confirmed that there is a good correlation between the geophysical results and the geotechnical results as presented in this study.

Table 5: Engineering Classification of the Subsoil in the Study Area using Plasticity Index (after Adeyemi and Oyediran, 2004).

Soil Sample	Plasticity Index Value	Plasticity Index Range	Index Classification	Cassangrade Plasticity Classification
B	4.5	>10	Low	Low Plasticity/Low Compressibility, High Competence
E	12.7	10-20	Medium	Medium Plasticity/Medium Compressibility, Moderate Competence
A, C and D	21.3, 24.7 and 34.0 (21.3-34.0)	>20	High	High Plasticity/High Compressibility, Low Competence

5.6.1 Grain Size Distribution

A summary of the geotechnical results is presented in table 6. The percentage passing sieve 0.075 mm ranges from 26.7 – 73.3. Typical particle size distribution curves obtained from the study area is presented in (Fig. 14). The soil distribution curves for the samples A-E show that the soil contained a good representation of the various grain sizes (Cassagrande, 1982). Hence, the soil samples are classified to be well graded (non-uniform). Samples B and E have values of 26.7% and 27.5% passing No. 200 sieve. The samples have < 50% passing No. 200 (0.075 mm) sieve which indicate that they are more coarse grained soil than samples A, C and D with > 50% passing sieve 0.075 mm with percentage values of 73.3%, 64.6% and 54.7%. These soils are described as clay of high plasticity (Tables 4). Samples B and E falls within the 30% maximum recommended by Federal Ministry of Works and Housing (FMWH), 1972 while Samples A, C and D falls above the 30% maximum recommended value for a foundation material. Samples B and E suggest low swelling potential with eventual rise in water table, low compressibility, higher unconfined Compressive Strength and Shear Strength under loading conditions. Therefore, based on the analysis presented in table 6, soil samples B and E are considered to be good and hence, more suitable as foundation geo-material, sample C is considered to be fair while samples A and D are rated as poor.

5.6.2 Mineralogy

The casangrade chart (Fig. 15) is indicative of the possible existence of a variety of soil types in the study area. Figure 15 shows that all the soil samples lie below the U-line. The U-line defines the possible upper limit of plasticity of a given soil. The soil samples plot on the chart show that most of the soils plot between the A-line and the U-line. The soil sample plot on the chart tends to indicate the presence of illite clay type. This implied that the presence of illites clay type may impart be indicative of a fairly stable soil for siting engineering foundation. From the Casangrade chart (Fig. 15) samples B and E plots on the low plasticity zone. Sample D plots on the intermediate plasticity zone while soil samples A and C plots on the high plasticity zone (Fig. 15). This result indicates that soil samples B and E is non-cohesive (sandy) and it is friable. Soil sample D is less cohesive and fairly friable while soil samples A and C is actually cohesive (i.e. clayey) and non-friable. Hence, samples B and E may be considered to be more stable and more competent sub-grade material than samples A, C and D. These results corroborated the grain size distribution analysis result.

Table 6: Summary of the Geotechnical Results

Geotechnical Properties	Sample A	Sample B	Sample C	Sample D	Sample E	Range of values Recommended for fodation material by Federal Ministry of Works and Housing (FMWH) Nigeria 1972, 1974, 1992 and 2000.	Head (1982), and Lambe and Whitman (1979)	Jegede, 1999 and 2000.	Max. Recommended value for subgrade material by Brink et al,. 1992, Madedor, 1983 and Adeyemi, 1992.	Engineering Foundation Suitability Rating
Natural Moisture Content (%)	18.8	8.0	16.4	12.4	7.1					
% passing Sieve 0.075 mm	73.3	26.7**	64.6	54.7*	27.5**	≤ 35%				Good
Liquid limit	62.2	31.3**	54.7	44.4*	32.3**	≤ 40%				Good
Plastic limit	28.2	26.8	24.7	21.3*	19.6					
Plasticity Index	34.0	4.5**	30.0	23.1*	12.7**	0 -1 2 – 4 5 – 9 10 – 20				Good Fair Poor V. Poor
Linear Shrinkage	11.4	5.0**	11.4	9.3*	5.7**	≤ 9.0			≤ 10	Good
Coefficient of Consolidation, C_v (m^2/year)	0.309	0.339	0.314	0.321	0.339		< 0.01 Very low 0.1 – 1.0 Low 1.0 – 10 Medium 10 – 100 High > 100 V. High			Excellent Good Fair Poor V. Poor
Coefficient of Volume Compressibility (MPa^{-1})	0.475	0.112**	0.405	0.326*	0.118**		< 0.05 Very low 0.05 – 0.1 Low 0.1 – 0.3 Medium 0.3 – 1.5 High > 1.5 V. High			Excellent Good Fair Poor V. Poor
Compression Index	0.105	0.020**	0.084	0.065*	0.118**		0.15 – 0.075 Low 0.3 – 0.15 High > 3.0 V. High			Good Fair Poor
Optimum Moisture Content (%)	22.3	9.4	20.1	16.4	8.3					
Maximum Dry Density (Kg/m^3)	1304	1914**	1431	1595*	1974**	> 2121 1958 – 2121 1795 – 1958 1632 – 1795 1142 – 1632		Best foundation soil has high MDD at low OMC		Excellent Good Fair Poor V. Poor
Unconfined Compressive Strength, q_u (KPa)/ KN/m^2	155.1	276.0**	175.7	199.1*	270.6**	> 200 150 – 200 100 – 150 < 100				Excellent Good Fair Poor
Shear Strength (KN/m^2)	78	138**	88	100*	135**	100 – 150 100 – 150 75 – 100 50 – 75				Excellent (Stiff) Very Good Good Fair

Sample with ** Asterisks' is Good Sample with * Asterisk' is Fair Sample with no Asterisk' is Poor

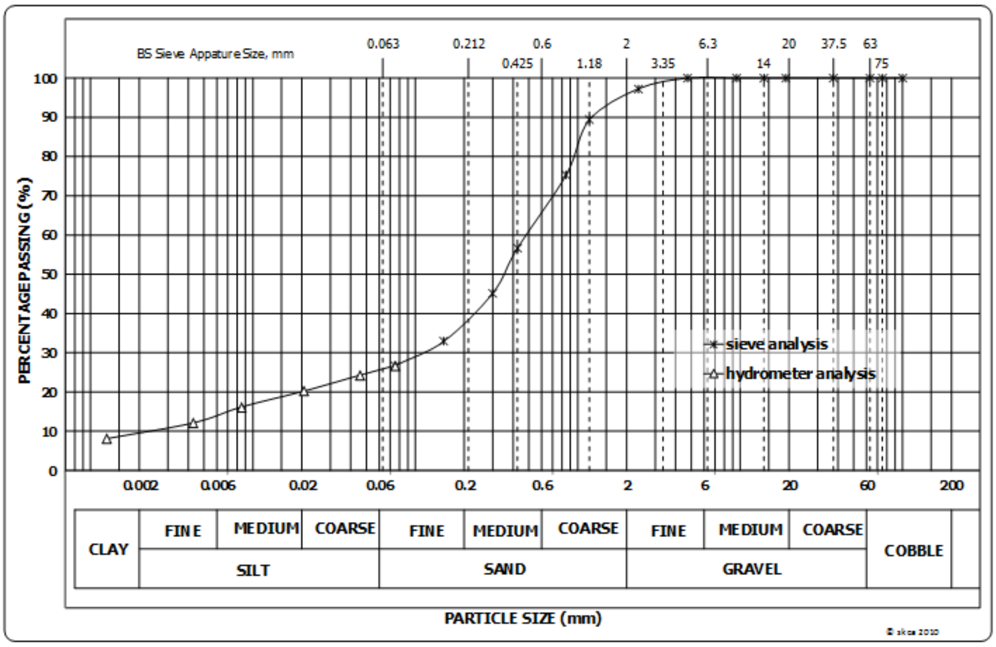


Fig.14. :Typical Particle Size Distribution Curve for Sample B

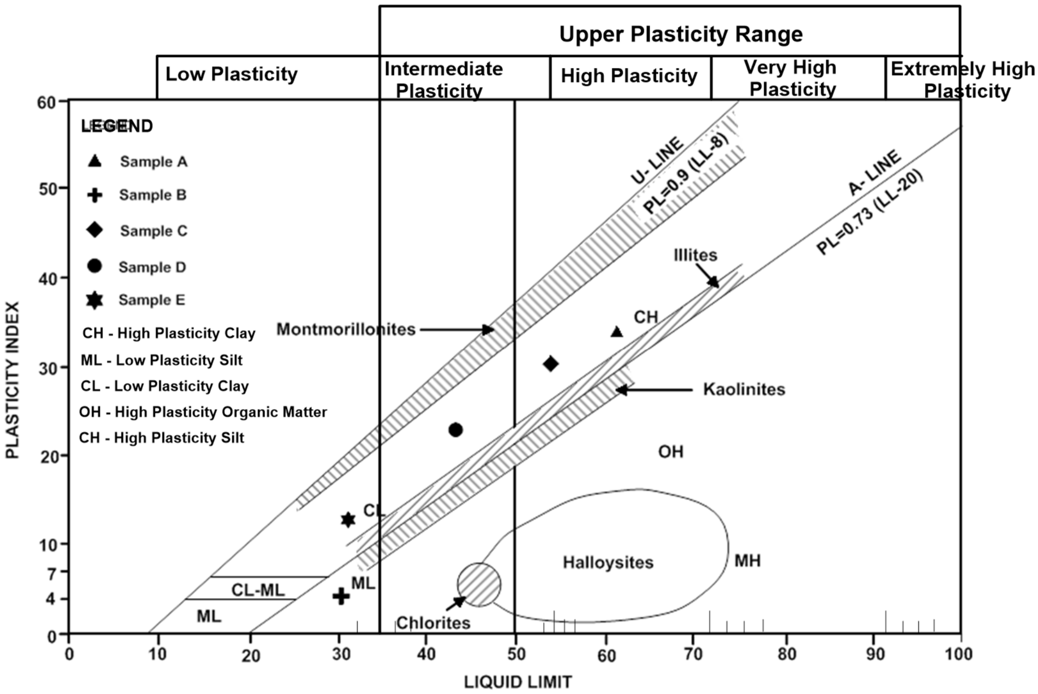


Fig. 15: Plasticity Chart for the Soil Samples in the Study Area

5.6.3 Atterberg Limits Test

Table 6 present a summary of the liquid and plasticity limits of the soil samples. The liquid limit (WL), plastic limit (WP) and plastic index (PL) values for the five (5) soil samples obtained from the investigated area range from 31.3-62.2%, 19.6-28.2% and 4.5-34.0% respectively. The FMWH (1974) recommended liquid limit of 40% and plastic index of 12% for sub-grade material (Adejumo, *et al.* 2015). Samples B and E have lower liquid limit values of 31.3 and 32.3% which is lower than the maximum 40% recommended while the values for samples A, C, and D 62.2%, 54.7% and 44.4% respectively, are higher than the maximum 40% specified value table 6 and (Fig. 15). Plasticity index of samples B and E are 4.5% and 12.7% fall within the maximum 12% recommended while the values for samples A, C, and D are 34.0%, 30.0% and 23.1% respectively, are observed to be higher than the maximum 12% specified value table 6.

Based on the ranges of plasticity index (PI%) as shown in (Fig. 15) and the swelling potential shown in Table 7 (Ola, 1982), the swelling potential of the soil samples from the study area can be categorized. Samples A and C have plasticity index (PI %) values of 34.0 and 30.0. These samples have a characteristic high swelling potential. This implies the presence of clay soil which may be subject to alternate expansion and contraction with season and with a consequent floor heaving and eventual foundation failure. Sample D has plasticity index (PI %) value of 23.1% with a swelling potential rating of medium range. This shows that sample D will be more competent sub-soil material than sample A and C to host engineering foundation. Samples B and E have plasticity index (PI%) values of 4.5% and 12.7% respectively (Fig. 15). The swelling potential is characterized to be of low level rating. This implies that the samples contain more sand than samples A, C, and D. This signifies that samples B and E are better foundation materials than soil samples A, C and D from the study area.

Table 7: Potential Expansiveness of the Soil (After Ola, 1982)

Plasticity Index (PI %)	Swelling Potential
0 – 15	Low
15-25	Medium
25-35	High
Over 75	Very High

5.6.4 Linear Shrinkage

The linear shrinkage values of the soil samples generally range from 5.0% – 11.4% table 6. Brink et al., 1992 recommended that soils with linear shrinkage of 8% to be indicative of inactive, inexpansive and hence a good foundation material. Soil samples B and E have shrinkage values of 5.0% and 5.7% which falls within the 8% recommended. Samples A and C have11.4% each while sample D has 9.3%, which are higher than the 8% minimum recommended value. This result suggests that samples B and E may not be susceptible to swelling with seasonal changes in wetness that is characteristic of the tropical region. Jegede, 1999, observed that the lower the linear shrinkage, the lower the tendency of the soil to shrink when subjected to desiccation.

5.6.5 Natural Moisture Content

The natural moisture content of the soil samples generally range from 7.1% – 18.8% table 6. It was observed that soil samples B and E have the lowest moisture content values of 7.1% and 8.0% while samples A, C, and D has higher values of 18.8%, 16.4% and 12.4% respectively. The observed values show that the lower the natural moisture content of a soil, the more competent the soil. Therefore, samples B and E can be adjudged to be a better foundation material than samples A, C and D at the investigated site.

5.6.6 Maximum Dry Density

The Maximum Dry Density (MDD) of the soil samples generally range from 1303.9 – 1973.59 Kg/m^3 at Optimum Moisture Content (OMC) of 8.3 – 22.3% table 6. Typical consolidation curve is shown in (Fig. 16). It is observed that soil samples B and E have the highest MDD values of 1913.96 kg/m^3 and 1973.59 kg/m^3 at lower OMC values of 9.4% and 8.3%. Samples A, C and D have lower MDD values of 1303.9 kg/m^3, 1431.11 kg/m^3 and 1594.81 kg/m^3 at relatively higher OMC values of 22.3%, 20.1% and 16.4% than samples B and E. It can be inferred from this study that soil with higher MDD at lower OMC is considered to be a better foundation material as earlier observed by (Jegede, 1999).

5.6.7 Consolidation Test

5.6.7.1 Coefficient of Consolidation (Cv)

Deformation characteristics on the five (5) soil samples A-E obtained from the investigated area were determined in accordance to the BS 1377 (British Standard Institution, 1990) as summarized in table 6. Typical curve of coefficient of consolidation (Cv) for sample E is presented in (Fig. 17). The coefficient of consolidation (Cv) for the soil samples A – E generally range from 0.309 – 0.339 (m^2/yr). The observed values falls within those obtained for other soil types elsewhere in the world Table 8. Table 9 contains typical values of coefficient of consolidation (Cv) (Lambe and Whitman, 1979) and the corresponding rate of consolidation and typical material. The values of coefficient of consolidation (Cv) m^2/yr obtained for samples A – E in the study area which range from 0.31-0.34 m^2/yr has a characteristic low rate of consolidation. This indicates that all the soil samples contained > 25% clay (table 8).

5.6. 7.2 Coefficient of Volume Compressibility (Mv)

The Coefficient of Volume Compressibility (Mv) for samples A – E generally varies from 0.112 – 0.475 (m^2/MN or MPa^{-1}) table 6. Table 10 show typical values of the coefficient of volume compressibility (Mv) (Head, 1982) and the corresponding compression behaviour. Samples A, C, and D has values that range from 0.325 – 0.475 (m^2/MN or MPa^{-1}). This is an indicative of high compressibility table 10. Samples B and E has a compressibility values which range from 0.112 – 0.118. These samples are characterized by medium compressibility and low compression behaviour (table 10). This compression behaviour is indicative of sandy clay material. This suggests that samples B and E are considered better foundation material and of higher strength than samples A, C and D.

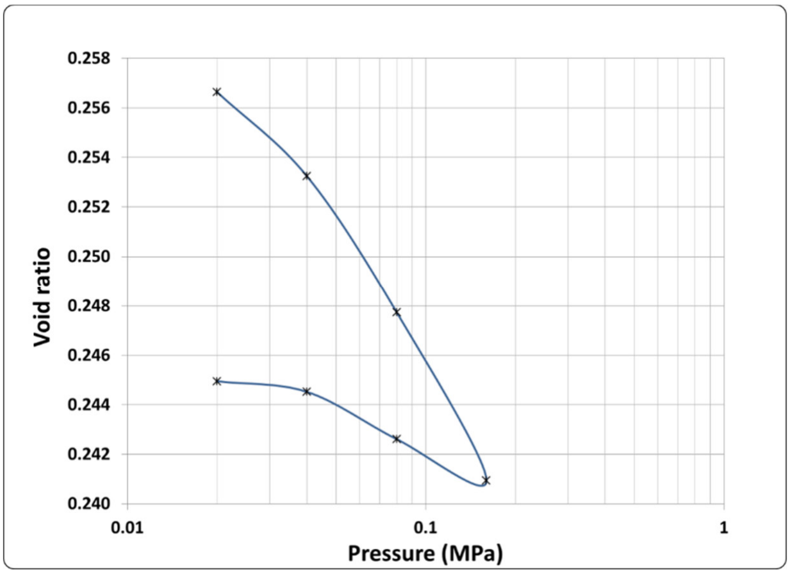
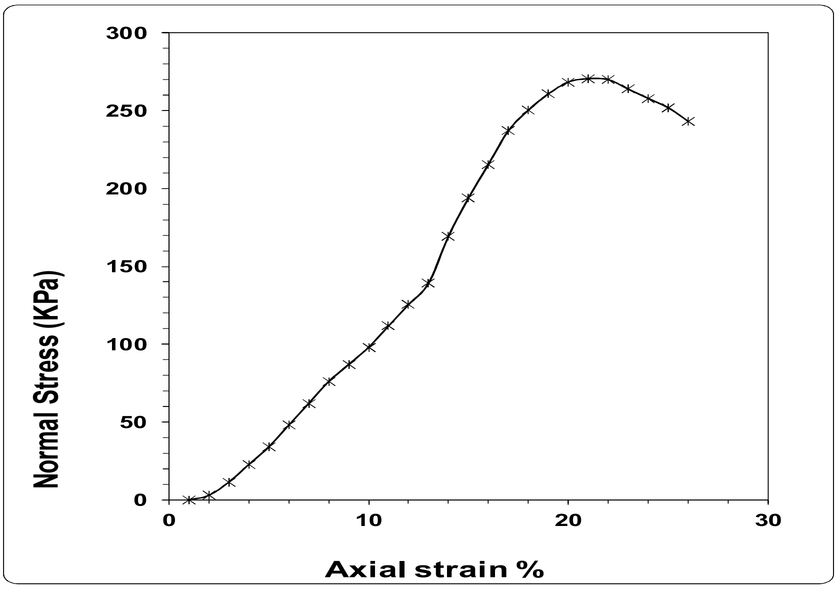
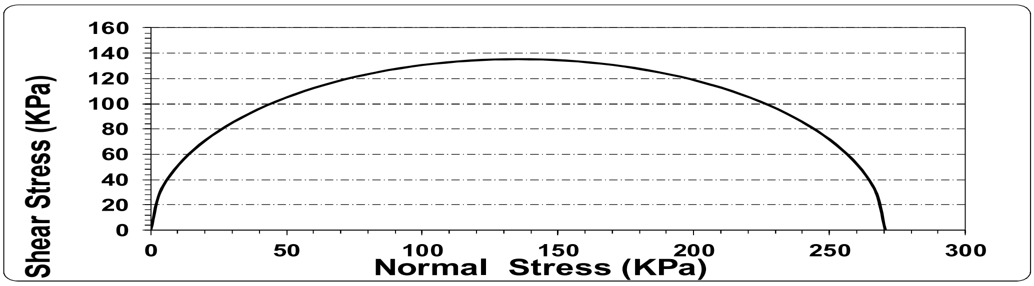


Fig. 16: Typical Consolidation Plots for Sample E

Unconfined Compression Test			
LOCATION:		SAMPLE No.:	S 5
DEPTH OF SAMPLE:		SAMPLE TYPE:	Undisturbed
		DATE:	10/09/2013





Unconfined compressive strength (kPa)	270.6
Bulk Density (kg/m^3)	2137.4
Moisture Content (%)	8.30
Dry Density (kg/m^3)	1973.59
shear strength (kPa)	135.29

Fig. 17: Typical Unconfined Compressive Strength Plots for Sample E

Table 8: Engineering Suitability Ratings for Soil Samples from the Study Area Based Upon Unified Soil Classification (USCS) Groups. Das (2002).

Unified Soil Classification Typical Names	USC group Symbol	Soil Sample No.	Suitability for Building Foundation
Inorganic Clays of high plasticity, fat clays, silty clays, elastic soils	CH	A and C	Poor (Swelling)
Silty sands, poorly graded sand-silt mixtures.	SM	B	Good (Density important)
Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	CL	D	Poor (Swelling)
Clayey sands, poorly graded sand-clay mixtures.	SC	E	Good (Density Important)

Table 9: Typical Values of the Coefficient of Consolidation (Cv) after Lambe & Whitman (1979)

Coefficient of Consolidation, C_v (m^2/year)	Rate of Consolidation	Typical Material
< 0.01	Very low	
0.1-1.0	Low	>25% clay
1-10	Medium	15-25% clay
10-100	High	<15% silt
> 100	Very high	

Table 10: Typical Values for the Coefficient of Volume Compressibility (Mv) after Head (1982).

Coefficient of Compressibility, (MPa^{-1})	Compressibility	Compression Index, C_c	Compression Behaviour	Clay Type
<0.05	Very low	>3.0	Very high	Soft clay
0.05-0.1	Low	0.3-0.15	High	Clay
0.1-0.3	Medium	0.15-0.075	Low	Sandy clay
0.3-1.5	High			
>1.5	Very high			

5.6. 8 Unconfined Compressive Strength

The Unconfined Compressive Strength (UCS) of soil samples observed in the study area generally range from 155.1 – 276.0 KN/m^2 table 6. Figure 17 presents a typical Unconfined Compressive Strength (UCS) plot for the study area. The results show that all the soil samples A – E have higher values than the acceptable minimum value of 130 KN/m^2 recommended by the FMWH, 1977. This shows that the subsoil within the investigated site can be adjudged to be of high strength and hence, considered to be competent as foundation material.

5.6.9 Shear Strength

The Shear Strength of the soil samples A – E tested ranges from 77.55 – 138 KPa table 6. Samples B and E have the highest shear strength of 138.02 and 135.29 KPa while samples A, C and D have relatively lower values of 77.56 Kpa, 87.8 KPa and 99.5 Kpa. It can be inferred from the observed values that soil samples B and E are more competent geo-materials to support the proposed structures than samples A, C and D.

5.6.10 Cross Plot of the Coefficient of Consolidation (C_v) m^2/yr and the Liquid Limit (LL%).

A cross plot of the coefficient of consolidation (C_v) m^2/yr and the Liquid Limit (LL%) is presented in (Fig. 18). Fig. 18 can be used to establish a relationship between the coefficient of consolidation (C_v) m^2/yr and LL% for the study area. The graph in (Fig. 18) shows that the value of the coefficient of consolidation (C_v) m^2/year decreases by -0.001 value as the value of LL% increases within the investigated area. There is a good correlation value of 0.98 existing between the coefficient of consolidation (C_v) m^2/yr and the LL% (Fig. 18). The gradient of the graph in (Fig. 18) is -0.001. This implies that for any increase in LL%, the coefficient of consolidation (C_v) m^2/yr decreases by -0.001 for the soil sample in the study area.

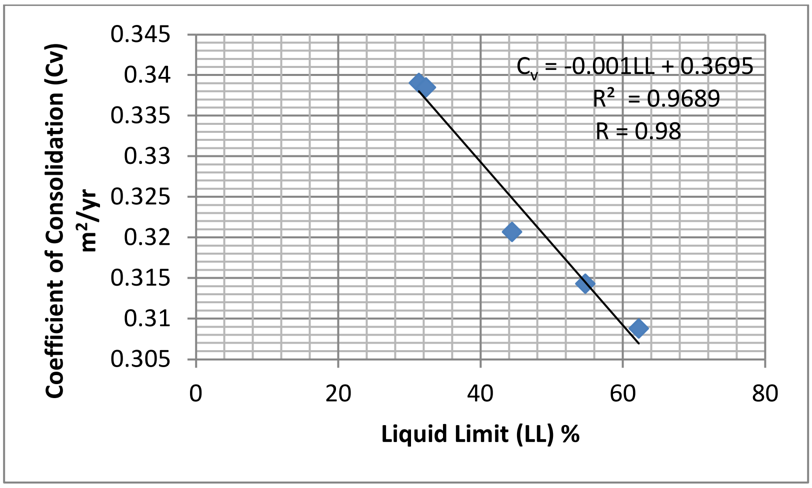


Fig. 18: Plot of Coefficient of Consolidation (C_v) m^2/yr against Liquid Limit (LL%)

6. Conclusions

Integrated geotechnical and geophysical methods have been used for subsoil characterization of parts of the new stadium complex Akure, Southwestern Nigeria. This is with the aim to determine its geotechnical competency for location of civil infrastructures. Five magnetic and three dipole-dipole profiles were undertaken at station separation of 10 m along the traverses and a total of twenty-one (21) Vertical Electrical Sounding (VES) utilizing the Schlumberger array were carried out within the investigated area. Geotechnical tests were carried out on five (5) soil samples obtained from the study area. The magnetic profiles delineated characteristic one to two negative peak amplitude anomalies that are typical of thin dipping dyke models (suspected to be fractures, shear zone, faults or geological boundaries) along Traverses 1 – 5. The identified fractured/fault zones constitute weak geologic zones that are inimical to civil engineering structures. The 2-D geomagnetic section was used to delineate overburden thicknesses which vary from 5-15 m along the Traverses in the study area. The geoelectric section, 2-D resistivity images and the resistivity maps show that both the topsoil and the weathered layer identified low resistivity zones that are diagnostic of clay, sandy clay and partly weathered/fractured basement rock that are characteristic of weak geo-materials which can constitute a major threat to the stability of proposed civil engineering structures in the study area. These zones are areas where engineering foundation are not desired. The fracture/fault zones delineated by the magnetic and geoelectric methods are potentially weak areas that may precipitate failure of civil engineering foundation and an eventual collapse of the building sited on them in the investigated area.

The geotechnical tests carried out on five (5) soil samples obtained from the study area includes: grain size distribution, consolidation, atterberg limits, grain size analysis and unconfined compression tests. The particle size distribution curved obtained for soil samples A-E in the investigated area show that the soil samples A-E are classified to be well graded (non-uniform). It was observed that samples A and C have >50% passing sieve No. 200 and classified by AASHTO as clay soil of high plasticity and adjudged to be a poor foundation material. Sample D has value of 54.7% passing sieve No. 200, and it is classified as fine-coarse grained soil. AASHTO described the soil to be silty clay of intermediate plasticity and considered to be fairly suitable as foundation material. Samples B and E have percentage values of 26.7% and 27.5% passing sieve No. 200. This indicates that they are more coarse grained soils. AASHTO described the soil samples as silty clay of intermediate plasticity) and it is classified to be fairly suitable as foundation material. Summary of the geotechnical classification of the subsoil in the study area using plasticity index show that samples A, C and D have high index classification and are characterized by high plasticity/high compressibility and consequently, are considered to be of low engineering competence. Also, samples B and E are characterized by low-medium index classification and are characterized by low-medium plasticity/low-medium compressibility and are rated to be of moderate-high civil engineering competence. The results obtained from the particle size distribution show a good correlation with the plasticity index classification obtained in the study area. However, soils with higher liquid limit or plasticity index have lower electrical resistivity values and hence low competence. A summary of the soil analysis results show that soil samples B and E are considered to be good and more suitable as foundation material, sample C is considered to be fair while samples A and D are considered as poor foundation material. The other factor that can as well be used in the assessment of soil/subsoil competence is the geologic structures and lineament density. This study shows that there is good correlation between the geophysical and geotechnical results obtained from this study. It can therefore be concluded that the subsoil in the investigated area is characterized by low, moderate and high competence. The study concludes that integration of geophysical and geotechnical methods can be successfully used to characterize the near subsurface soils for the location of civil engineering structures.

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