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Delineating Depth to Bedrock using Electrical Resistivity: An Implication for Foundation Design in Engineering Site Investigation

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Abstract

The present study applied geophysical method to engineering site investigation with the aim to delineate depth to bedrock and determine area that can induce structural failure. Direct current electrical resistivity method using Vertical Electrical Soundings (VES) field procedure and Very Low Frequency Electromagnetic (VLF-EM) profiling techniques were adopted. Twelve (12) VLF-EM profiles and twenty-four (24) VES stations were occupied. The result of VLF/EM was unable to map genuine linear structure because significant peak positive threshold fall below 20 %. Four geoelectric units comprising of topsoil, lateritic/weathered layer, partially weathered layer and fresh bedrock with resistivity values which ranged from 88.4 to 680.3 Ωm, 45.9 to 597.3 Ωm, 27.9 to 1309.1 Ωm, and 625.5 to 16,450.6 Ωm; and layer thicknesses from 0.4 to 4.2 m, 1 to 15.1 m, 2.9 to 15.1 m were delineated respectively. The bedrock configuration presents a highly undulating structural pattern due to differential weathering, with depth to bedrock range between 5.0 and 22.0 m. The study location is underlain with competent earth materials of good bearing capacity and resistivity values generally > 100 Ωm except in the bedrock depressions in the north-east, east and southern flanks where resistivity values are < 100 Ωm. Foundation of engineering structure may be designed to avoid the high-risk zone in the bedrock depressions. Shallow foundation design is recommended for small to medium engineering structures in the study but deep foundation design is recommended in the bedrock depression filled with low resistivity earth materials.

Keywords: Bedrock depression, Depth to bedrock, Foundation, Geo-electric units, Structural failure, Very low frequency-electromagnetic

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Introduction

Records of structural failure associated with expansive soils are common in Western Canada, Colorado, Texas, Wyoming, India, Nigeria, Israel, South Africa, and to some extent South Australia, California, Utah, Nebraska, South Dakota and Blyth [1, 2]. It often results in fatalities and loss of economic valuables. In Nigeria cases of collapsed buildings have been recorded in major cities. Some of these failures were attributed to structures founded on concealed refuse dump sites, buried river channel, swelling clays, fracture zone, incompetent soils, heterogeneous nature of the sub-base and sub-grade materials, poor quality of building materials, old age of building, failure precipitated by differential settlement, differences in expansion and compression coefficients of construction materials, relative changes in the shapes and sizes of saturated soils, an extra loading more than that originally designed for a structure to carry and errors in structural design [3-15]. The foundation of any structure is meant to transfer the load of the structure to the ground without causing the ground to respond to uneven and excessive movements. In order to achieve this, most buildings are supported by pads, strips and rafts or piles foundation type. Subsurface instabilities leading to foundation failure is of great concern to engineers and geoscientists around the world.

Delineating depth to bedrock is a major key to engineering site investigation for foundation design to militate against building collapse due to geology and structural failure. Bedrock (fresh basement) is the massive competent and impermeable subsurface rocks with high bearing capacity. Therefore, bedrock is a good base for foundation of built engineering structure. There are two ways to determine depth to bedrock namely: direct method and indirect method. The direct method involves the drilling of boreholes to obtain direct information from the subsurface geology, through analysing thickness of stratigraphic horizons in the boreholes to determine depth to bedrock and also extrapolate between boreholes [16]. However, interpolation between data points in spatial model can result to notable inaccuracies on regional scale [17] because drilling of boreholes are generally insufficient and expensive, which needs external drift data to give a good result of the interpolated data between wells where there is no data [18].

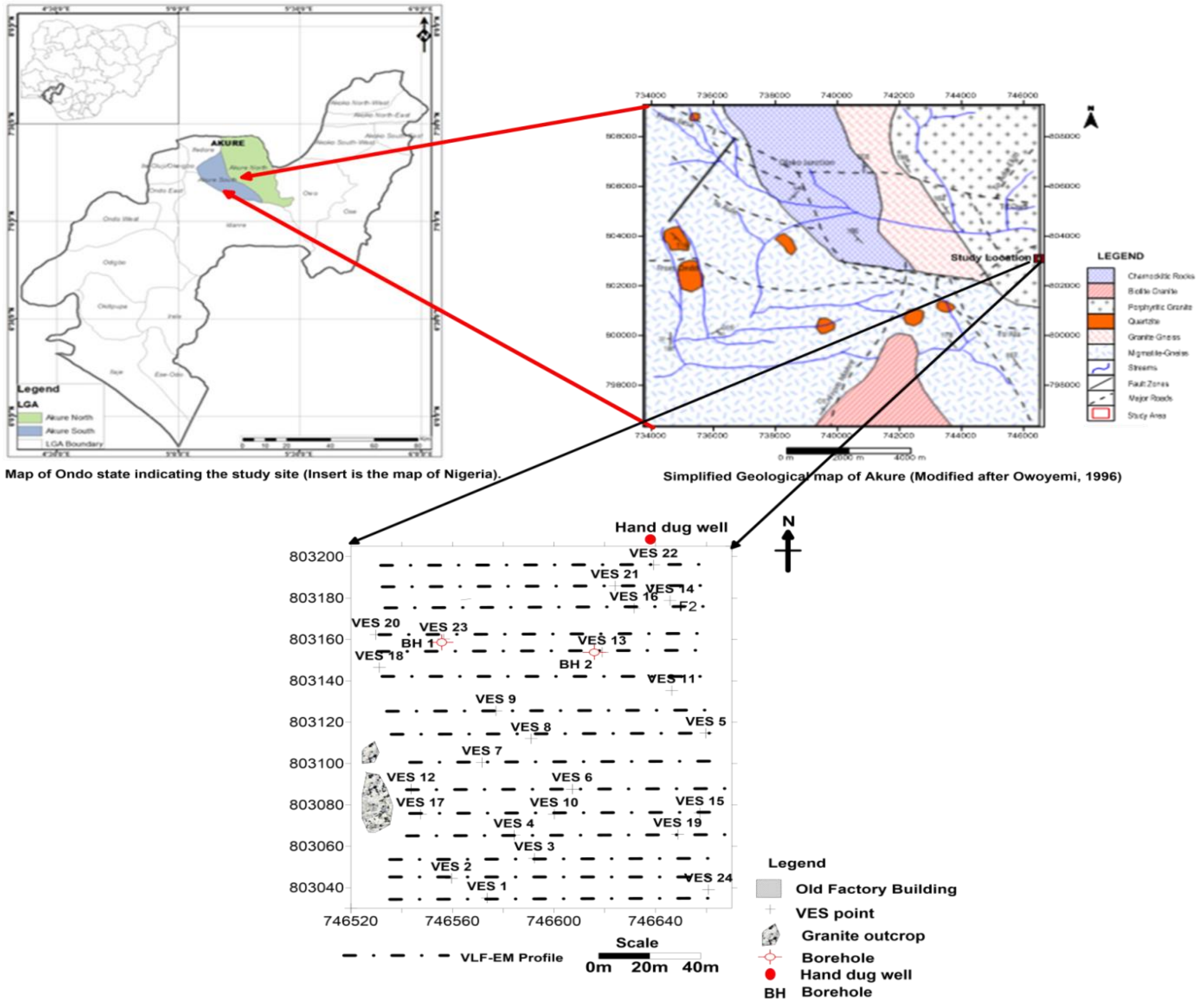
Hence, geophysical methods are more appropriate because it is an indirect, non-invasive, and can cover large area on regional scale with relatively low cost

[17]. One of the most commonly used geophysical methods is electrical resistivity involving Very Low Frequency - Electromagnetic (VLF-EM) and Vertical Electrical Soundings (VES) techniques that can give good result in basement environment. VLF-EM is very useful in mapping efficiently near surface conditions including faults and fractures which are conductive zones. These identified conductive zones can serves as guides for acquisition of Vertical Electrical Soundings (VES) data because it is very challenging to apply VLF-EM technique alone without combination with other geophysical technique. VES is responsive to the subsurface fluid content [19]. It has been adopted for groundwater development [20], foundation design and construction in shale and sandstone derived soils [11] and environmental investigation [21]. According to Olorunfemi and Okhue [22], bedrock relief map shows bedrock topography and its structural disposition, it follows therefore that the knowledge of the subsurface geologic sequence and bedrock relief map prior to construction work provides valuable information required to prevent possible structural failure. The aim of this paper is to explore the application of Very Low Frequency Electromagnetic (VLF-EM) and VES techniques for engineering site investigation which includes depth to bedrock determination and delineation of areas which can possibly induce structural failure of built engineering structure.

Materials and Methods

Description of the location, topography and geology of the study site

The study area is located along Akure-Oba-Ile road, Akure, South-western Nigeria (Fig. 1). It is situated between Latitudes 7^{o} 15’ 33.63” and 7^{o} 15’ 39.90” N, and Longitudes 5^{o} 13’ 56.97” and 5^{o} 14’ 02.05” E (Fig. 1). The topography is moderately undulating with elevation that ranges from 342.5 to 345.3 m above mean sea level. The area gently dips south, and is covered by cassava farm. The study area is underlain by crystalline rocks of the Precambrian Basement Complex of South-western Nigeria [23]. Porphyritic granite (Fig. 1) is the major rock type within the study area and is concealed by superficial residual soil in places. Outcrops of porphyritic granite are visible on the western part of the study site, a hand dug well on the north-east just outside the boundary wall; and two abandoned boreholes on the north-west and north-east of the study site (Fig. 1). Also, outcrops of laterite are prominent in the northern part of the study area.


Map of Ondo state indicating the study site (Insert is the map of Nigeria).

Simplified Geological map of Akure (Modified after Owoyemi, 1996)

Figure 1: Location map showing the survey layout of the study site

Materials

Satellite imagery of the location from Google Earth® was used for survey planning. The Ohmega resistivity meter with associated accessories, Garmin Global Positioning System (GPS), and ABEM WADI VLF electromagnetic equipment were used for data acquisition; while Karous and Hjelt [24] filter®, Win-Resist® and Surfer® were used for data processing, and modelling.

Methodology

Field observation and measurement

Field observation of the abandoned boreholes and measurements using echo sounder in the hand dug well were carried out to determine the water table and thickness of the overburden in the boreholes and well respectively.

Very low-frequency electromagnetic (VLF-EM)

The VLF-EM data were acquired on twelve traverses ranging from 120 to 140 m and oriented in the east-west direction with station separation of 10 m (Fig. 1). Raw real (RR) (or in phase and raw imaginary (RI) (or quadrature components) were measured in the VLF-EM survey. The raw real data were converted to filtered real where genuine inflections were transformed to peak positive anomalies and false infections become negative anomalies [24, 25]. The Filtered real (FR) and the filtered imaginary (FI) data were presented as profiles.

Electrical resistivity method

The electrical resistivity survey involving Vertical Electrical Soundings (VES) technique using the Schlumberger electrode configuration was adopted (Fig. 2). The current-current electrode spacing is symmetrically extended around the spread's center, while the potential electrodes stay constant for a time as shown in Fig. 2. The potential electrodes are moved when the distance between the current and potential electrodes multiplies; otherwise, the potential difference is too tiny to be precisely detected. The Schlumberger array is the typical electrode array appropriate for VES work. In the Schlumberger array, the distance between the potential electrodes must not be greater than two fifths (i.e., 40 %) of half the distance of the spacing (AB) of the current electrodes [26]. The half electrode spacing (AB/2) was varied from 1 to 100 m. Twenty-five (24) VES stations occupied were guided by the VLF-EM result to target areas characterized by peak positive filtered real anomalies. The acquired VES data were modelled using WinResist. The model results were interpreted as geo-electric units or layers. The delineated geo-electric units were sum up to generate overburden thickness (regolith), which was used to determine depth to bedrock.

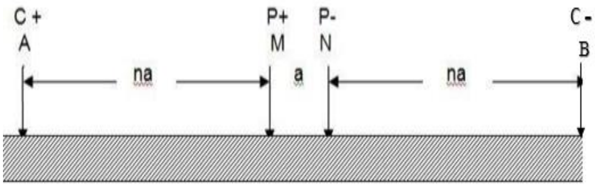


Figure 2: A typical Schlumberger array configuration

Results and Discussion

Geological measurement

The result of the two boreholes revealed they were abandoned due to low yield and the driller's report revealed that borehole one (BH1) overburden thickness is 11 m while borehole 2 (BH2) overburden thickness is 9 m. The hand dug well measured depth from the ground surface to the bedrock is 15 m in the study location.

VLF-EM profiles

Relatively high peak positive amplitude of the filtered real component identified at 110 m along Profile 2; 90 m along Profile 7 were non-conductive zones because they fall below a threshold of 20 % where significant peak positive amplitude begins (Fig. 3a and b) and may therefore probably be representative of linear features characterise as air filled or dry fractures. Negative filtered real anomaly identified at 90 m along Profile 2 and 60 m along Profile 7 is indicative of resistive structure, typical of bedrock horst (Fig. 3b).

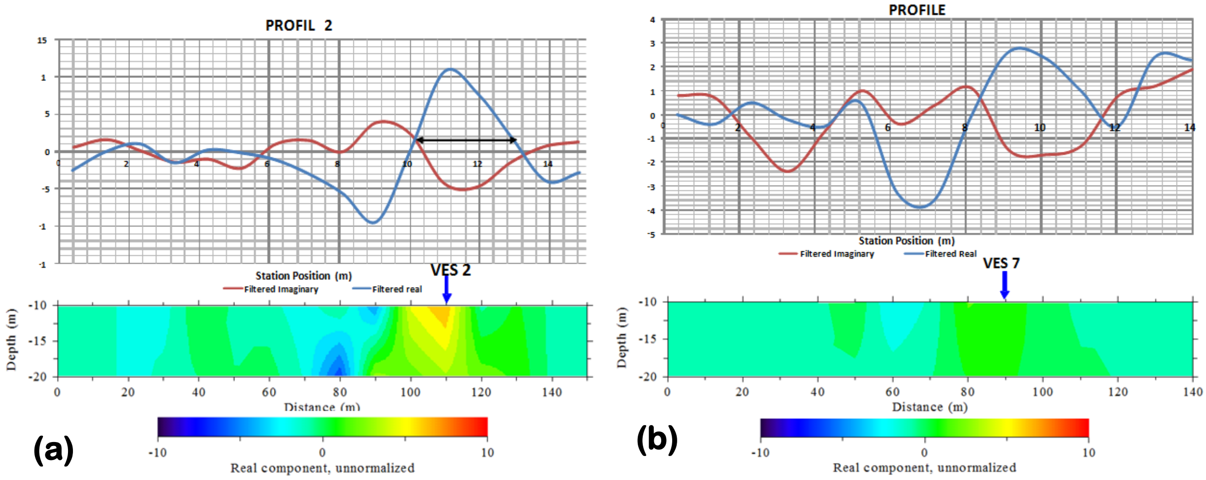
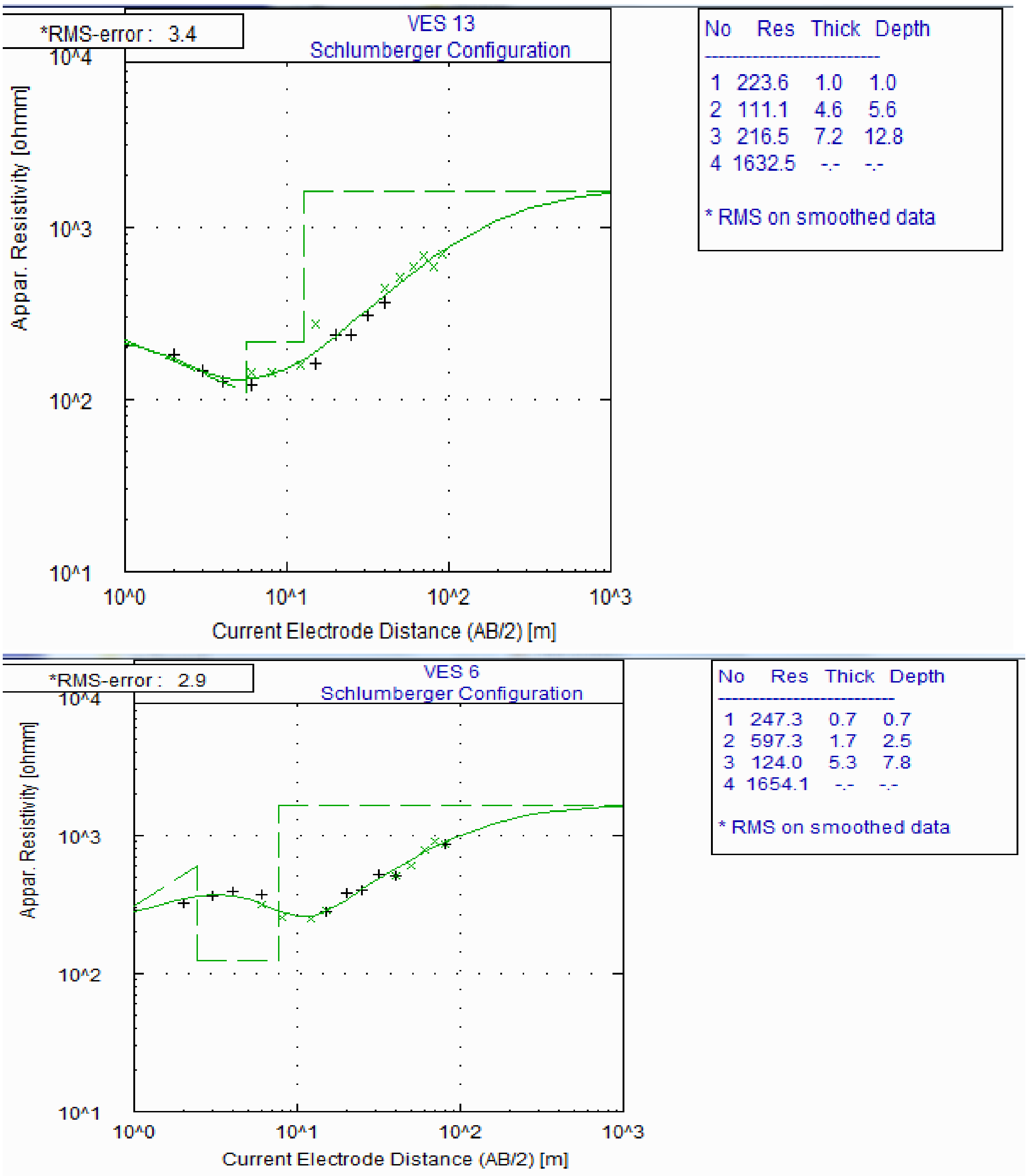


Figure 3: (a) VLF Profile 2 with VES 2 indicated on the profile; (b) VLF profile 7 with VES 7 indicated on the profile



No	Res	Thick	Depth
1	223.6	1.0	1.0
2	111.1	4.6	5.6
3	216.5	7.2	12.8
4	1632.5	-.-	-.-

No	Res	Thick	Depth
1	247.3	0.7	0.7
2	597.3	1.7	2.5
3	124.0	5.3	7.8
4	1654.1	-.-	-.-

Figure 4: Typical sounding curve types in the study area are (a) 'HA' curve type and (b) 'KH' curve type

Electrical resistivity soundings

Statistical analysis of the VES interpretation result revealed four resistivity type curves A, HK, KH, and HA, where HA type curve is more prevalence (Figs 4 and 5). The A and HA type were prominent in the central portion of the study area whereas KH and HK were mostly identified in the north-eastern, east and southern-eastern part of the study area.

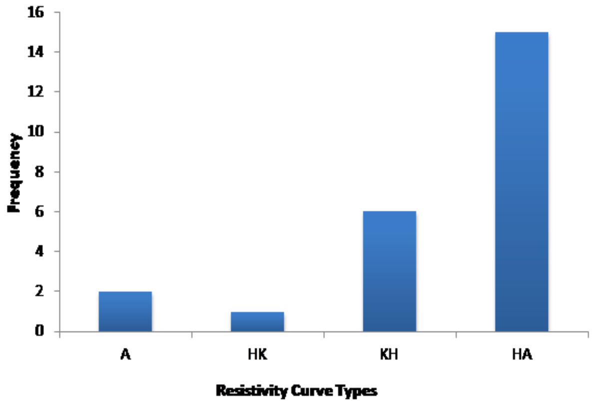


Figure 5: Distribution of the resistivity type curve obtained in the study area

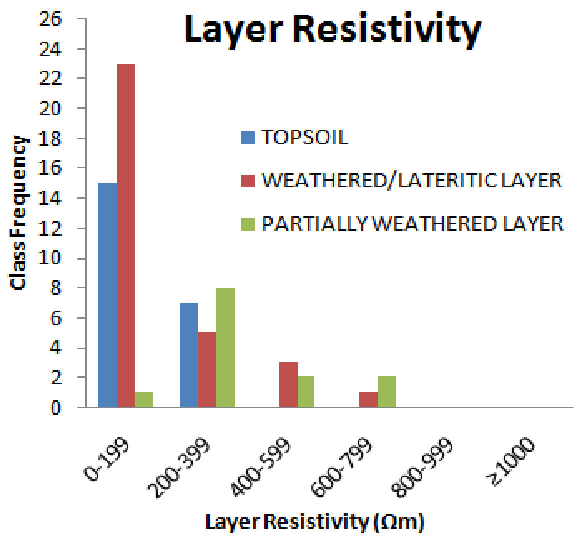


Figure 6: Histogram of the layer resistivity

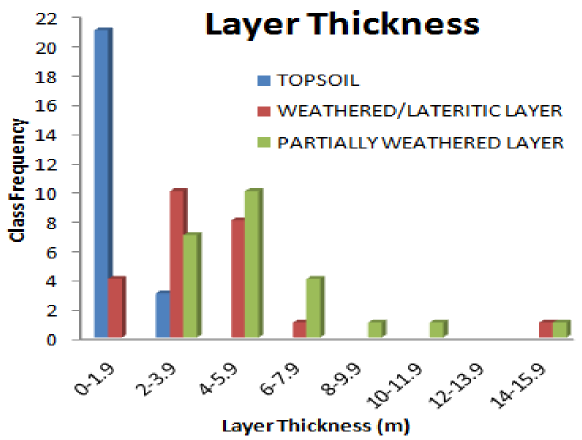


Figure 7: Histogram of layer thickness

Four geologic units were delineated, namely the topsoil, weathered/lateritic layer, partially weathered layer and the fresh basement. The topsoil has a moderate layer resistivity ranged from 88 to 247 Ωm (Fig. 6) that can be interpreted as dry sandy soil [27]. The topsoil is moderately thick with thicknesses ranged from 0.4 m to 2.1 m (Fig. 7), which are generally less than 1.9 m. The lateritic/weathered layer was characterized by resistivity values which ranged from 28 to 680 Ωm. The laterite formed a hardpan with K curve type which is observable as outcrop in the north and south of the study site. The weathered layer was clayey with low resistivity values generally less than 50 Ωm (Fig. 6), especially, in the western part around the granite outcrops where recorded resistivity values were less than 50 Ωm. The lateritic/weathered layer is fairly thick with thicknesses ranged from 1.0 to 15.1 m (Fig. 7). Inference derived from prevalent low resistivity values of weathered layered indicate that the layer may be incompetent to sustain engineering structure with moderate to high load because the weathered/lateritic layer resistivity is generally low except in the extreme north and south which formed scanty hardpan. Third geoelectric unit was interpreted as partially weathered layer. It is characterized by resistivity values which ranged from 139 to 755 Ωm, and thicknesses ranged from 2.9 to 15.1 m. The resistivity values of these layers are most frequent between 100 and 400 Ωm (Fig. 6). This is indicative of competent subsurface layer which may be relatively stable subsequent to loading. The resistivity of the fourth geoelectric unit was generally above 1000 Ωm, which represent fresh basement bedrock with high bearing capacity. These VES results revealed that the subsurface is made up of competent earth materials capable of supporting engineering structures except in few isolated areas, in the eastern (VES 19, 5, 22) and western (VES 20, 17) flanks (Fig. 1), with low resistivity that may be less competent probably due to the presence of conductive clay materials.

Geoelectric columnar section

The geoelectric columnar section 1 (Fig. 8) relates VES 17, 7, 9, 13, 16, and 22 (Fig. 1) in the southwest to northeast direction. The topsoil is fairly thick from the south towards the north and it is truncated in the northern part by an outcrop of laterite at VES 16. The laterite unit extends southward beneath the topsoil in VES 13. The topsoil beneath VES 13 is 1.2 m thick with resistivity value of 116 Ωm, which was underlain by laterite of 2.4 m thick with resistivity value of 210 Ωm and 4.1 m thick weathered layer with resistivity of 48 Ωm. The 2.4 m thick laterite can serve as a foundation base for medium engineering structures without causing settlement in the underlying weathered layer. VES 16 is underlain with 0.8 m thick and 439 Ωm laterite outcropping on the surface and 6.2 m thick weathered layer with resistivity value of 179 Ωm and 5.1 m thick of a partially weathered layer with resistivity value of 702 Ωm. These subsurface earth materials underneath VES 16 were interpreted as competent foundation base that can support engineering structures because of its moderate high resistivity values.

The weathered unit was observed to increase in thickness towards the south-western flank but thin beneath VES 9 with the layer thicknesses ranged from 1.0 to 15.1 m. A basement depression was observed at the VES 7 which may be due to differential weathering causing a significant depth of weathered materials. The bedrock depression is composed of topsoil with resistivity values of 231 Ωm, weathered layer with resistivity value of 229 Ωm and partially weathered basement with resistivity value of 591 Ωm. It is observed that the resistivity values beneath the VES 7 show a moderately competent material with good bearing capacity. Basement rock is shallowest beneath VES 9. It is overlain by 2.0 m thick topsoil with resistivity value of 90 Ωm and 1.0 m thick weathered layer with resistivity value of 136 Ωm (Fig. 8). The shallow basement with moderate resistivity values of the topsoil and weathered layer suggests a competent subsurface. The depth to bedrock varies between 5.0 and 23.0 m, thus revealing undulating bedrock.

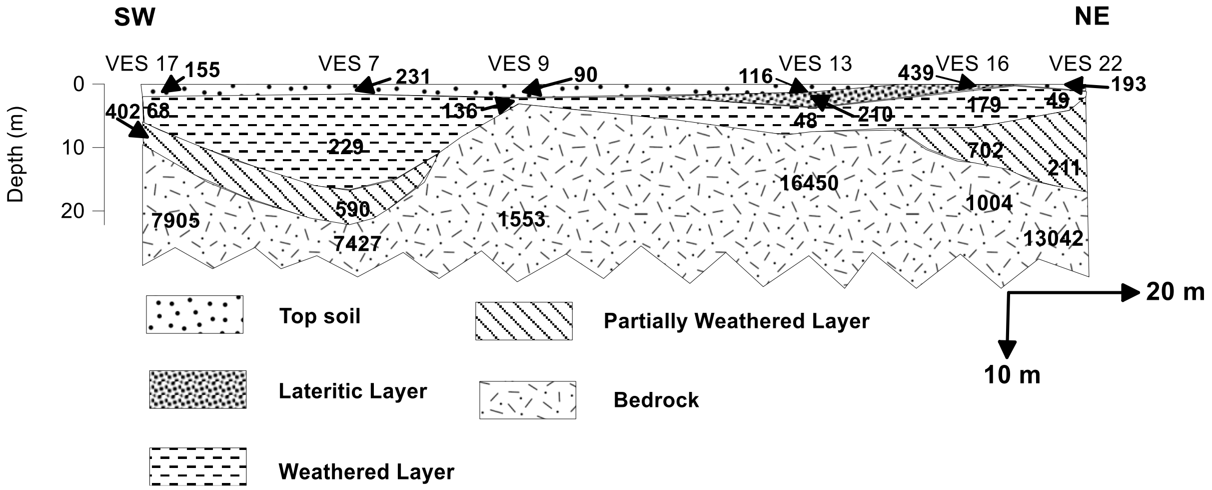


Figure 8: Geo-electric section across VES 17, 7, 9, 13, 16, and 22 in the SW-NE direction

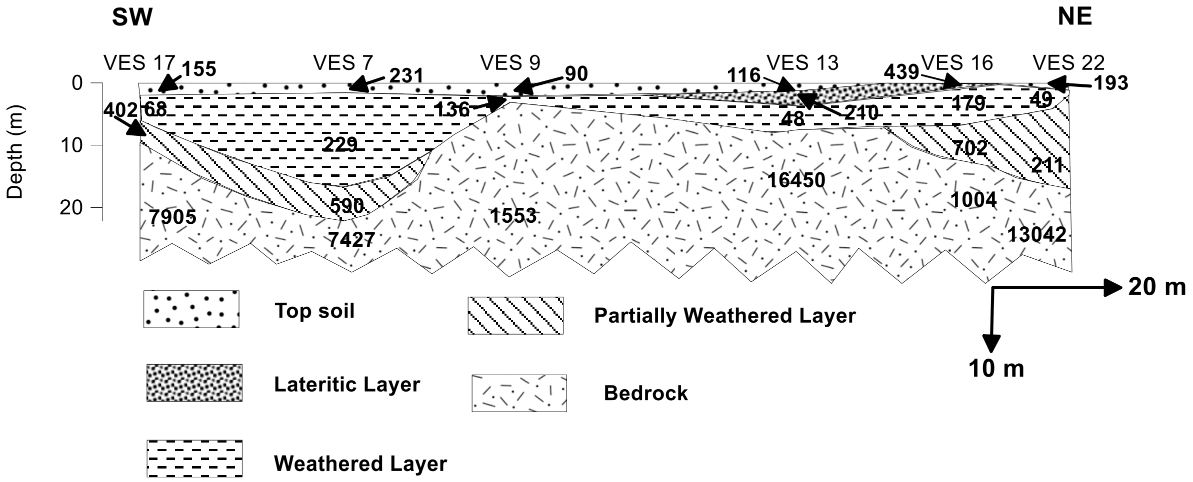


Figure 9: Geo-electric section across VES 20, 23, 9, 8, 6 and 19 in the NW-SE direction of the study site

Geoelectric columnar section 2 (Fig. 9) is oriented in the northwest-southeast direction and relates VES 20, 23, 9, 8, 6 and 19 (Fig. 1). The geologic units (topsoil and weathered layer) overlaying the bedrock were observed to be continuous across the VES stations but laterites and partially weathered layers were found to be localised beneath VES 20, 6 and VES 23, 19 respectively across the section. The laterites are covered by the topsoil beneath VES 20 and VES 6 with thicknesses of 1.0 and 1.7 m respectively. The topsoil resistivity values are generally above 100 Ωm, except at VES 9 and VES 20 with recorded resistivity values of 90 and 88 Ωm respectively.

The weathered layer is characterized by relatively low resistivity of 28 Ωm and thickness of 3.9 m in the north-western flank beneath VES 20. This low resistivity material may be inimical to failure when loading because of low bearing capacity. However, the south-eastern flank is characterised by materials with resistivity greater than 90 Ωm and moderately thick > 4.0 m, which is indicative of fairly competent materials of moderate bearing capacity. The low resistivity areas beneath VES 20 may be potential risk zones prone to failure due to settlement when loading because it is considerably less thick. The partially weathered layers beneath VES 23 in the north-west and VES 19 in the south east have resistivity values of 370 and 367 Ωm respectively. It can be concluded that the study area has undergone differential weathering based on this study. The average depth to bedrock varies between 5.0 and 22.0 m, thus revealing bedrock with undulating structural disposition.

Depth to Bedrock

Table 1 shows the delineated depth to bedrock (overburden thickness) for each VES station in the study site. The depth to bedrock ranged from 5 to 22 m in VES 20 and VES 7 respectively. Isopach map (Fig. 9) was produced from the result of delineated depth to bedrock (Table 1). Fig. 10 shows the variation in thickness of the overburden across the study location. Two prominent structures were identified side by side in the centre of the study with red and blue dash lines as closed structures. The structures were oriented in the north-south direction of the study. Structure identified with red dash lines is a deeper structure trending north-south through the centre of the study with the overburden thickness ranging from 10 to 22 m.

Whereas, structure identified with blue dash lines is a shallower structure centred in the study area with overburden thickness ranging from 6 to 9 m. The overburden materials are thickest in VES 7 with thickness of about 22 m and shallowest at VES 20 with thickness of about 5 m. There is an observable porphyritic granite outcrop in the western flank that may be responsible for the shallow overburden thickness with thickness generally less than 9 m, however, the eastern flank is generally deep with thicknesses greater than 12 m. It can be inferred that the area has undergone differential weathering due to uneven distribution of the depth to bedrock in the area.

Table 1: Shows the delineation of depth to bedrock from VES interpretation results

S/N	VES Station	Overburden Thickness (Depth to Basement) (m)
1	1	11
2	2	10
3	3	10
4	4	8
5	5	17
6	6	8
7	7	22
8	8	9
9	9	6
10	10	10
11	11	9
12	12	9
13	13	8
14	14	12
15	15	13
16	16	12
17	17	10
18	18	9
19	19	13
20	20	5
21	21	11
22	22	17
23	23	13
24	24	14

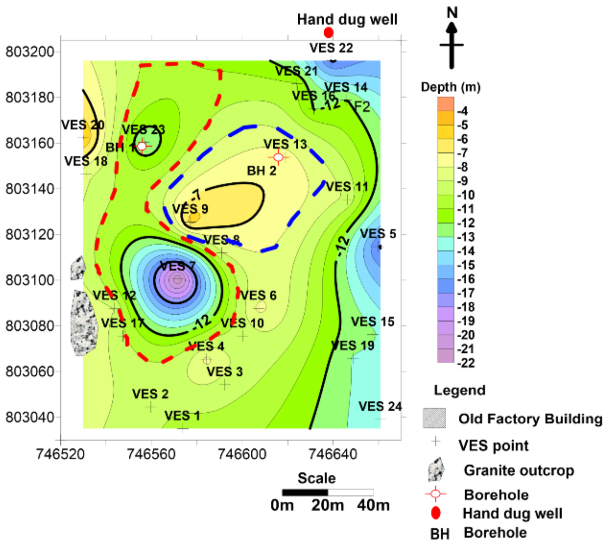


Figure 10: Isopach map of the study area

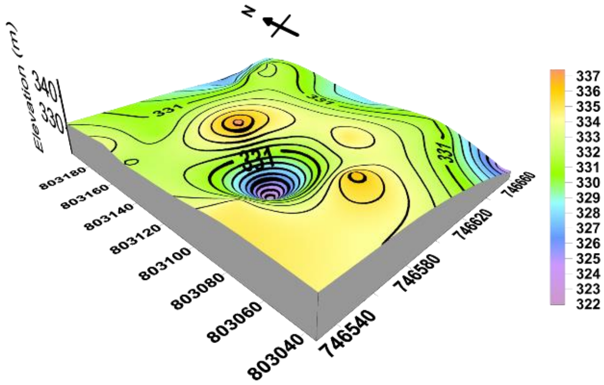


Figure 11: The basement relief map of the study area

Figure 11 reveals the structural configuration and disposition of the bedrock. The shallowest point is located at the central part of the study. Major bedrock depressions were identified in the centre, north-eastern and eastern flank of the study area. These identified zones of depression were areas that can induce structural failure if they are filled with low resistivity earth materials. However, these zones were filled with moderately high resistivity materials (Figs 8 & 9) with good bearing capacity that can support loading of built engineering structure. Therefore, construction of small to medium engineering structures in the site is feasible by excavating materials with low bearing capacity and filled with materials with high bearing capacity. However, major engineering structure such as high rise building may require crafted foundation design.

Conclusion

Application of geophysical method has been used in engineering site investigation for delineating depth to bedrock in parts of Akure, South-western Nigeria. VLF-EM method was adopted to map geological features that can induce failure but it is unable to map genuine linear structure such as fracture and fault zones because significant peak positive threshold fall below 20 %. The electrical resistivity method delineated four geologic units interpreted as topsoil, lateritic/weathered layer, partially weathered layer and fresh bedrock. Depth to bedrock varies from 5.0 to 22.0 m, indicating an undulating bedrock relief. The average depth to bedrock is generally less than 12 m, which corroborated the result obtained from direct information measured from the BH 1 – 11 m, BH 2 – 9 m and hand dug well – 15 m. The isolated depression in bedrock relief map is filled with relatively high resistivity subsurface materials of 231 Ωm topsoil, 229 Ωm weathered layer and 591 Ωm partially weathered basement and these moderately high resistivity values were indicative of a competent earth materials of good bearing capacity. The study revealed that the depth to bedrock is less than 12 m in the central portion and composed of competent earth materials capable of supporting small to medium engineering structures with shallow foundations. The north-western, eastern and southern flanks were areas delineated to induce structural failure because of the presence of low earth materials; however, geologic features such as faults and fractures cannot be identified in the bedrock depressions. Therefore, pile foundation design is recommended in these bedrock depressions to transfer the load to the bedrock.

Conflict of interest: We declare that there is no conflict of interest.

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