

EFFECT OF DYNAMIC PATTERN OF THE SAPROLITIC ZONE AND ITS BASEMENT ON BUILDING STABILITY: A CASE STUDY OF A HIGH-RISE BUILDING IN OGBOMOSO

T. A. ADAGUNODO^{1*}, L. A. SUNMONU¹ AND A. A. ADENIJI¹

¹Department of Pure and Applied Physics, Ladoko Akintola University of Technology, Ogbomoso, Nigeria.

AUTHORS' CONTRIBUTIONS

This work was carried out in collaboration among authors TAA, LAS and AAA. Authors TAA and LAS designed the study and wrote the protocol. Authors TAA and AAA anchored the geophysical field work, data acquisition, data processing and preliminary data analysis. Author TAA managed the literature searches and produced the initial draft. Author LAS supervised the investigation from initial stage to the point of submission for publication. Author TAA managed the corrections from International Knowledge Press' reviewers while all the authors read and approved the final manuscript.

Received: 1st May 2015

Accepted: 27th May 2015

Published: 9th June 2015

Original Research Article

ABSTRACT

The importance of stability and the resistance to horizontal forces imposed on a building cannot be overemphasized as the alarming rate of structural failure such as roads, buildings, dams and bridges has become more intense throughout the globe. These failures have been traced to subsurface instability and its geological features. When building fails, it's usually goes with loss of lives and properties. The need for pre-foundation studies using geophysical approach has been found as the only remedy for this ugly incidence. This approach will map the subsurface in order to predict the nature of the proposed site for construction. A geophysical survey involving Electrical Resistivity Tomography (ERT) and Vertical Electrical Sounding (VES) were employed at a proposed site for high-rise building. This research was done in order to infer whether the subsurface is competent to withstand high-rise structure or not. The results of ERT and VES showed that the subsurface would not be able to withstand high-rise building in order to avert deadly collapse which might have happened in the investigated area in the future. However, the proposed high-rise building is hereby advised to be relocated to another site.

Keywords: Basement; building stability; competency; geophysical survey; saprolitic zone; subsurface.

1. INTRODUCTION

Saprolite is a chemically weathered rock that forms in the lower zones of soil profiles and represent deep weathering of the bedrock surface [1]. In another word, it is a soft earthy red or brown decomposed igneous or metamorphic rock that is rich in clay and formed in place by chemical weathering. Conditions

for the formation of deeply weathered regolith include a topographically moderate relief flat enough to prevent erosion and to allow leaching of the products of chemical weathering. A second condition is long periods of tectonic stability; tectonic activity and climate change can cause erosion. The third condition is humid tropical to temperate climate. Subsurface investigations employing geophysical techniques are of paramount importance in assessing the suitability

*Corresponding author: Email: taadagunodo@yahoo.com;

of an area for the construction of buildings, bridges, dams, among others. Nigeria in the past two decades has witnessed the collapse of several buildings under construction or shortly after construction. It is common knowledge that these buildings, among other reasons, collapse because appropriate geophysical investigations were not carried out to determine the nature of the subsurface structures. Most of these buildings were built on soils that have inadequate bearing capacity to support the weight of the building [2].

The geology of an area is critical in assessing its suitability for the type of building to be erected. Near-surface soil may consist of expansive clay that expands or shrinks as a result of change in moisture content [3]. Movement of foundation may occur if the clay moistening and drying is not uniform. Subsurface geological features such as fractures, voids, small depth of bedrock, near – surface depth to water table are among the common constraints to building constructions, especially to their foundations.

The geophysical studies provide the geotechnical information required in the engineering design in order to enhance the strength and stability of buildings or structures. The use of electrical resistivity imaging to address a wide variety of hydrological, environmental and geotechnical problems is increasingly becoming very popular. The 2D electrical resistivity imaging is now being used to detect fractures and cavities in the subsurface, geotechnical investigations for buildings, roads, bridges and dams. The method can also be used for delineating archeological features, locating surface utilities and for monitoring pollution seepage through the earth's subsurface. The method has been proven to be an effective tool for indentifying anomalies and defining the complexity of the subsurface geology [4].

It has become obvious that 1D electrical method had been improved to a two dimensional imaging of the subsurface [5]. However, the Vertical Electrical Sounding (VES) method is a depth sounding galvanic method and has proved very useful in groundwater studies as well as estimation of overburden thickness [6-8]. It has helped to estimate the saprolitic zone as well as the nature of the bedrock in any given area.

This study has been able to integrate vertical electrical sounding (or electrical drilling) and electrical resistivity tomography techniques together. The later was done by employing Wenner Alpha array while the former was done by Schlumberger configuration in order to check the subsurface competency for high-rise building in the study area. The two configurations are from electrical resistivity survey method. The

resistivity study requires the introduction of an artificial current into the ground through point electrodes or long line contacts. The potential in the earth (ground) due to the introduction of the current into the ground is measured using two potential electrodes which are planted on the ground surface. Since the current is measured as well, it is possible to determine the apparent resistivity of the subsurface. This however makes the resistivity method more superior (at least theoretically) to all the other electrical methods [9]. It is important to note that, deviations from the pattern of potential differences expected from homogenous medium, provides information on the form and electrical properties of subsurface inhomogeneities. These two configurations have been adopted by Joel [10].

1.1 The Study Area

The study was conducted at a proposed site for construction of guest house (high-rise building) in Ogbomoso (Fig. 1). The geophysical survey was conducted in the month of October. It is located between latitude 08°07' N and longitude 04°14' E. The study was aimed at understanding the thickness of the saprolitic zone and competency of the bedrock in the subsurface. This was done in order to recommend whether the study area is competent enough for the construction of the guest house or not. High-rise building that is constructed on peat/clayey zone or unstable superficial soil formation might experience differential settling of buildings and their eventual or sudden collapse in the future. Clayey formation is understood for its ability to retain water with poor transmissivity. During the raining season, clay retains water and dries off during dry season which might set the building constructed on it in to motion since it's a rigid body. The study area lies in the Precambrian basement complex of southwestern Nigeria. Locally, Quartzite, Quartz-Schist, Undifferentiated Gneiss and Migmatite are found in the study area and its environs (Fig. 2).

2. MATERIALS AND METHODS

The purpose of electrical survey is to determine the subsurface resistivity distribution whereby measurements are made on the ground surface. From these measurements, the true resistivity of the subsurface can be estimated. The ground resistivity is related to various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock. Electrical resistivity surveys have been used for many decades in hydrogeological, mining and geotechnical investigations. More recently, it has been used for environmental surveys. The resistivity measurements

are normally made by injecting current into the ground through two electrodes (C1 and C2 in Fig), and measuring the resulting voltage difference at two potential electrodes (P1 and P2). From the current (I) and Voltage (V) values, an apparent resistivity (ρ_a) value is calculated.

$$\rho_a = K \frac{V}{I} \quad (1)$$

Where k is the geometric factor which depends on the arrangement of the four electrodes. The figure above shows the common arrays used in resistivity surveys together with their geometric factors. Resistivity meters normally give a resistance value, $R = \frac{V}{I}$, so

in practice the apparent resistivity value is calculated by

$$\rho_a = KR \quad (2)$$

The calculated resistivity value is not the true resistivity of the subsurface, but ‘an apparent’ value which is the resistivity of a homogeneous ground which will give the same resistance value for the same electrode arrangement. The relationship between the ‘apparent resistivity’ and the ‘true resistivity’ is a complex relationship. To determine the true subsurface resistivity, an inversion of the measured apparent resistivity values using a computer program software package will be used.

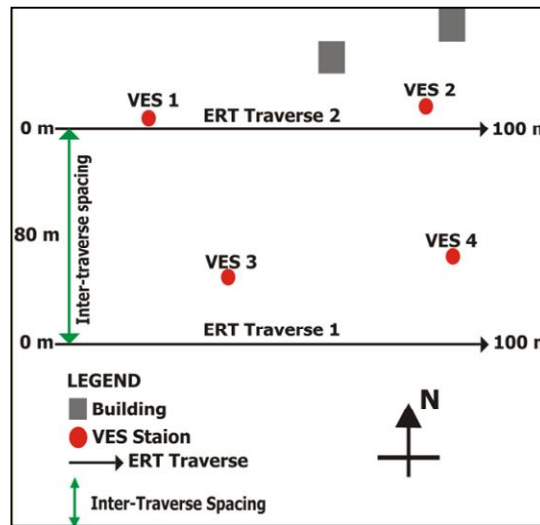


Fig. 1. The base map of the study area

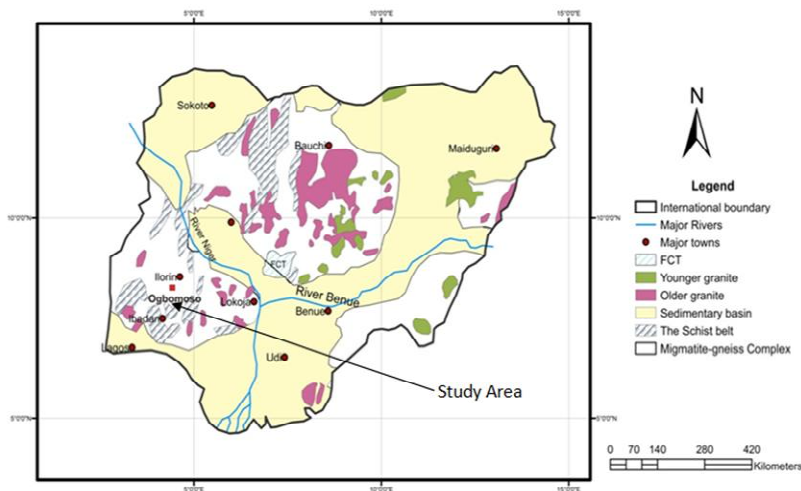


Fig. 2. Geologic map of Nigeria showing the study area [6]

The resistivity method has its origin in the 1920's due to the work of the Schlumberger brothers. For approximately the next 60 years, for quantitative interpretation, conventional sounding surveys [11] were normally used. In this method, the centre point of the electrode array remains fixed, but the spacing between the electrodes is increased to obtain more information about the deeper sections of the subsurface. Fig. 3 shows the conventional electrode array for electrical resistivity method.

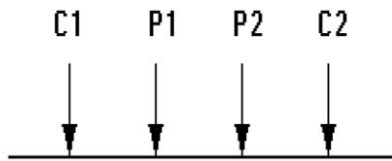


Fig. 3. A conventional four electrode array to measure the subsurface resistivity

One of the new developments in recent years is the use of 2-D electrical imaging/tomography surveys to map areas with moderately complex geology [12]. Such surveys are usually carried out using a large number of electrodes, 25 or more, connected to a multi-core cable. A laptop microcomputer together with an electronic switching unit is used to automatically select the relevant four electrodes for each measurement. At present, field techniques and equipment to carry out 2-D resistivity surveys are fairly well developed. The necessary field equipment is commercially available from a number of international companies. Fig. 4 shows the typical setup for a 2-D survey with a number of electrodes along a straight line attached to a multi-core cable.

In this research work, both Vertical Electrical Sounding (VES) and 2-D geoelectrical resistivity

surveys using both Schlumberger and Wenner arrays configuration respectively were adopted in this research work. The basic field equipment used for the study was PZ-02 earth resistivity meter which display apparent resistivity value digitally as computed from Ohm's law. The terrameter is powered by 12V D.C power source. Other materials that accompany the equipment are measuring tape, 4 hammers, metal electrodes where 4 metal electrodes was used for VES and ERT survey for current and potential electrodes respectively. Normal configuration procedure for ERT was followed during the geophysical survey such that the electrode spacing 'a' and the spacing increment were designed in order to give a better output of the research. In the VES where Schlumberger configuration was adopted, the four electrodes are positioned symmetrically along a straight line, the current electrodes on the outside and the potential electrodes on the inside. To change the depth range of the measurements, the current electrodes are displaced outwards while the potential electrodes in general, are left at the same position. When the ratio of the distance between the current electrodes to that between the potential electrodes becomes too large, the potential electrodes must also be displaced outwards otherwise the potential difference becomes too small to be measured with sufficient accuracy [11,13].

Two ERT traverses were occupied in the study area with a total length of 100.0 m each. The two traverses were measured in the same orientation (i.e. W-E) with an inter-traverse spacing of 80.0 m in order to juxtapose the signatures of the anomaly observed on traverse 1 with that of traverse 2 for civil engineering implications. The electrode spacing, 'a', are in order 1.0, 3.0, 6.0, 8.0, 15.0 and 20.0 m with interval or increment of 3 m for 'a' of 1.0, 3.0 and 6.0 m while 'a' of 8.0 m has increment of 4 m, and 'a' of 15.0 and

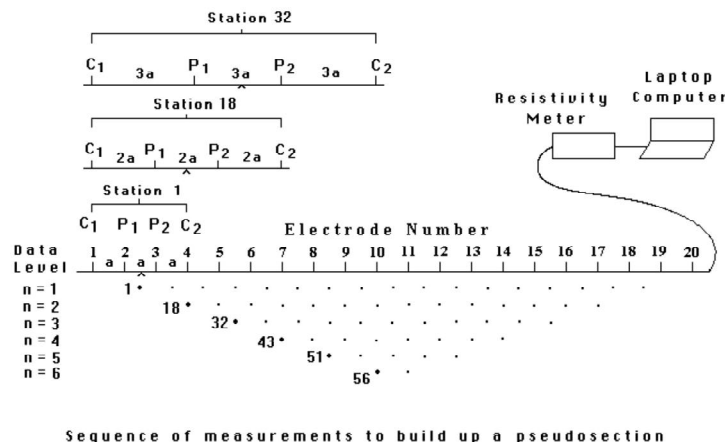


Fig. 4. 2-D measurement using wenner arrangement configuration [14]

20.0 m have increment of 5 m respectively. This gives a total data level of 6 for each traverse so that data points of 133 were observed per traverse line.

Four VES stations with half-current electrode separation ranging from 60.0 to 100.0 m were occupied on the study area in order to correlate the results of ERT to that of VES and to be able to determine the average overburden thickness of the study area. The resistance of the subsurface were recorded where the apparent resistivity were calculated using equation 2.

3. RESULTS AND DISCUSSION

The data was processed to generate 2D resistivity earth models using RES2DINV software developed by Loke and Barker [15]. This program uses a forward modeling subroutine to calculate apparent resistivity values from field data which are then inverted using a nonlinear Least-squares optimization technique [15]. The inversion routine in RES2DINV is based on the smoothness constrained least-squares method [16,17] but there is an option to use the quasi-Newton or the Gauss-Newton optimization techniques to implement the least-squares method.

The smoothness constrained least-squares is based on equation 3:

$$(J^T J + \mu(f_x f_x^T + f_z f_z^T))d = J^T g \quad (3)$$

where f_x is the horizontal flatness, f_z is the vertical flatness, μ is the damping factor, J is the Jacobian matrix of partial derivatives, d is the model perturbation vector, g is the discrepancy vector which contains the differences between the logarithms of the measured and calculated apparent resistivity values, and J^T is the transpose of J .

Both techniques at different iteration stages were combined to generate 2D resistivity models. The iterative process proceeds as follows: (1) the inversion routine produces an initial model of subsurface resistivity using the calculated apparent resistivity values and generates a response resistivity field based on the initial model and (2) it calculates a root mean square (RMS) value that describes the level of agreement between the synthetic and observed resistivity fields. A large RMS value usually $> 5\%$ indicates a poor fit. In this case, the initial model is adjusted iteratively until the RMS falls below the preset or desired threshold after which the iterative process is terminated. Due to the differential level of noise in the data, it was necessary to manipulate the damping factor in some cases to achieve stability in

the inversion process. The damping factor is a parameter whose value depends on the level of random noise present in the data [16]. A higher damping factor is needed for data with a high level of random noise and vice versa. Fig. 5a and 5b show the modeling of ERT from traverse 1 and traverse 2 respectively.

For the interpretation of Vertical Electrical Sounding, software called WinResist was used which generate or show the wavelike pattern of apparent resistivity and electrode spacing accordingly.

The resistivity values of 4 VES stations were determined and plotted on a double logarithmic graph paper. Partial curve matching was applied to the field data. Parameters such as apparent resistivity and thickness obtained from partial curve matching were further used as input data for computer iterative modeling named WinResist software which was developed by Vander Velpen and modified in 2004 [18]. The modeling produced the curves in Fig. 7a to 7d. However, the geoelectric section was obtained along two profiles with inter-VES spacing of 60 m. The profile orientation was in NW-SE direction. Profile 1 encapsulated VES 1 and VES 3 while profile 2 encapsulated VES 2 and VES 4 (Fig. 8a and 8b). Profile 1 has four lithology: topsoil, weathered layer, clayey zone, and fractured/fresh bedrock (Fig. 8a). Thick clayey zone close to the surface and fractured bedrock pose great risk to civil engineering construction. Clayey zone started from the depth of about 5 m deep. The average thickness of clay along profile 1 was 19.45 m which was considered too thick to be seated under high-rise building foundation. Beneath the clayey zone lies fractured bedrock which covered about half of the bedrock distribution in the study area. Profile 2 however has five lithology: topsoil, compacted sandstones, weathered layer, clayey zone, fractured bedrock/fresh bedrock (Fig. 8b). The region underlain with clayey zone and fractured bedrock are considered as incompetent for civil engineering purposes.

The 2D electrical resistivity section along Traverse 1 (Fig. 5a) is reflective of subsurface resistivity within the study area. From the inverse model section, the first layer in the structure has resistivity ranging from $50.0 \Omega m$ to about $547 \Omega m$. This layer is interpreted as the topsoil. The next layer is interpreted as weathered layer which is interwoven with a lateritic zone. An outcrop close to the study area (Fig. 6) further support the claim that laterite exist from the central to the end (central to east) of traverse 1. Another layer is interpreted as clayey zone due to its very low resistivity values (resistivity ranging from $17.4 \Omega m$ to $28.5 \Omega m$). This region might pose a

great risk to the civil engineering construction in the study area if it is not excavated. The trend of this clayey zone seems to be intercalated with a sandy clay or silty sand zone. Dynamic movement of this clayey zone during the two seasons in the study area might lead to the subsidence or collapse of the proposed high-rise building in the future. The last layer observed on the traverse is interpreted as fresh basement or competent bedrock. From Fig. 4a, it is observed that the overburden is generally thick except at the region where the basement is suspected to be an outcrop (distance 33.0 m to 44.0 m) which is too small for any civil engineering construction. Traverse 2 which is occupied in the same direction with traverse 1 with an 80.0 m inter-traverse spacing exhibit the same trend as that of traverse 1 (Fig. 5b).

The clayey zone observed from the central portion of the traverse extends from the depth of about 3.50 m to the base of the inverse model resistivity section. This means that the zone might extend beyond the depth of 20.0 m. This is not advisable for the construction of high-rise building!

The VES model resistivity curves are presented in Fig. 7a to 7d. The VES model resistivity interpretation was used to complement the inversion results of the 2D resistivity images. The four VES stations were randomly sounded in order to determine the thickness of the clayey zone, the overburden thickness and the nature of the bedrock in the study area. VES 1, 3 and 4 has QH-curve type while VES 2 has H-curve type.

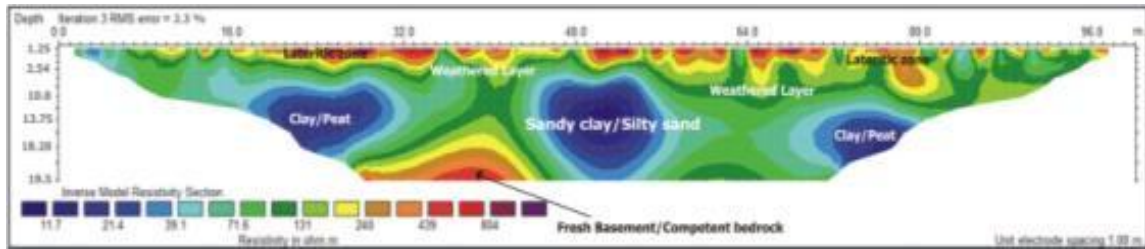


Fig. 5a. The inverse model resistivity section of traverse 1

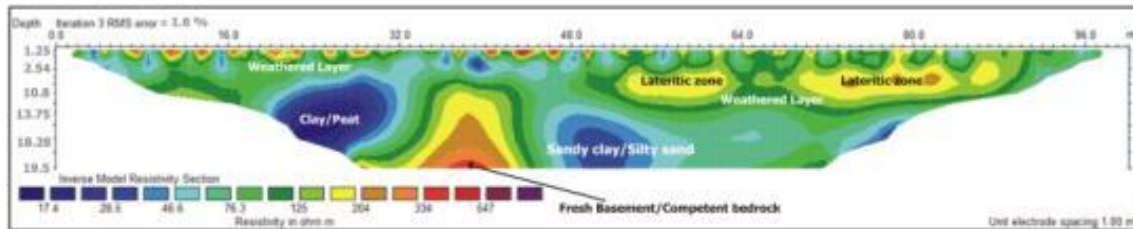


Fig. 5b. The inverse model resistivity section of traverse 2



Fig. 6. An outcrop that was found close to the study area

VES 2 and VES 3 are underlain with fresh bedrock/basement while VES 1 and VES 4 are underlain with fractured bedrock/basement. The resistivity of the first layer in VES 1, 3 and 4 depict that lateritic zone exist in the study area (resistivity ranging from $1082.3 \Omega m$ to $3619.4 \Omega m$). This further supports the claim of Fig. 6. The overburden thickness ranges from 17.8 m to 27.1 m with an average of 23.4 m. The clayey zone in VES 1 has a thickness of 17.3 m, VES 3 has thickness of 21.6 m and VES 4 has thickness of 14.5 m. This is considered as too thick for civil engineering construction

especially high-rise building. About 230.0 m away from the study area, a differential settlement was experienced on a certain building (Fig. 9) which was in the same orientation with the ERT traverse. This has further support the claim that though the topsoil seems to contain hard rocks, the layers beneath (i.e. the layer or layers before the basement) are not competent to withstand high-rise building. If this observation and the geophysical advice are neglected, it might lead to loss of lives and properties in the future. ‘Obedience is better than sacrifice’.

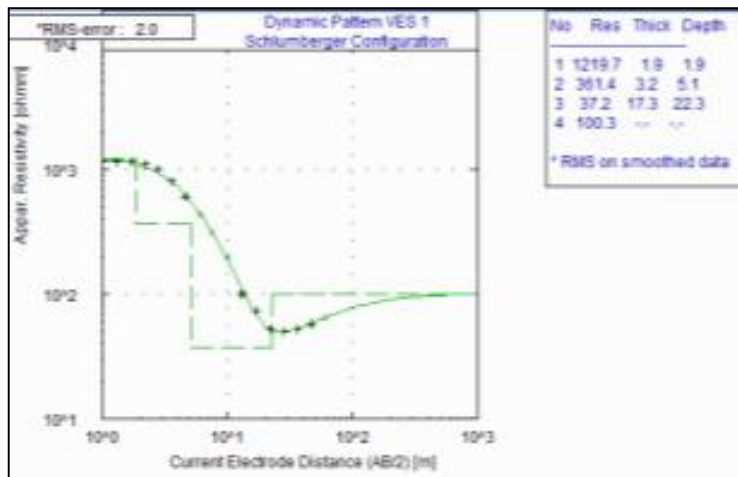


Fig. 7a. The modeled curve for VES 1

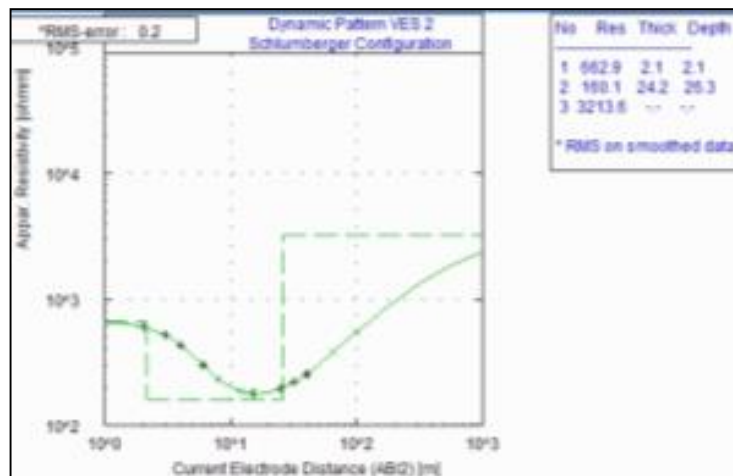


Fig. 7b. The modeled curve for VES 2

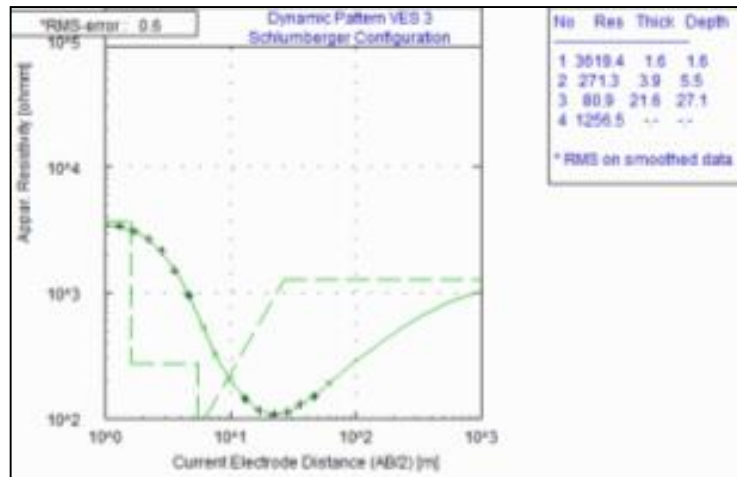


Fig. 7c. The modeled curve for VES 3

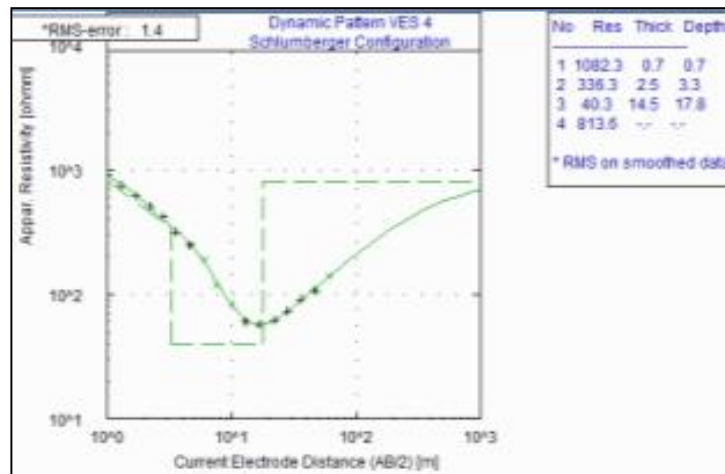


Fig. 7d. The modeled curve for VES 4

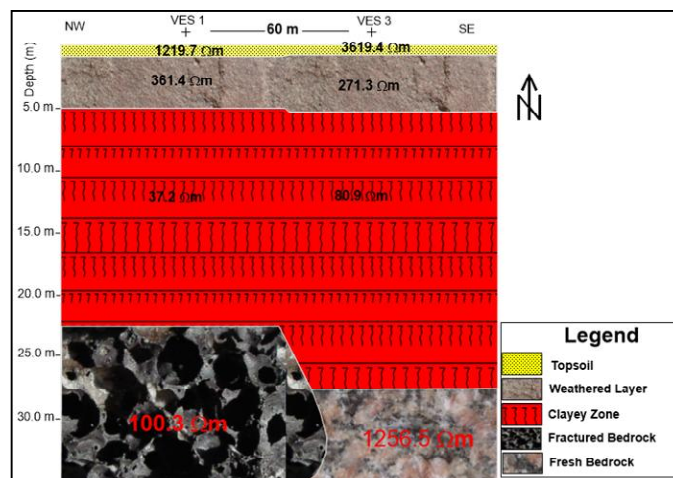


Fig. 8a. Goelectric section along profile 1

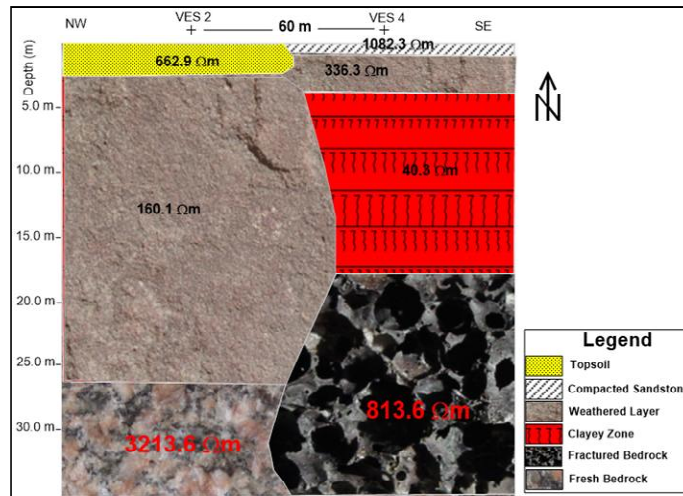


Fig. 8b. Geoelectric section along profile 2



Fig. 9. Samples of the affected structures close to the study area

4. CONCLUSION

2D electrical resistivity tomography (ERT) and 1D vertical electrical sounding (VES) techniques have been successfully used to investigate the suitability of the subsurface structures at the proposed site for the construction of high-rise building in Ogbomoso. This was with a view to detecting any geological features that may pose a serious problem to the building after construction. The 2D and 1D electrical resistivity data were acquired from the area using the PZ-02 earth resistivity meter. The acquired apparent resistivity data was interpreted using the Res2DINV software

and WinResist respectively. Results of the interpretation of the inverse resistivity models and modeled VES curves in conjunction with the known geology of the area showed that the saprolitic zone which lies above the bedrock consist of clay and weathered zone. The overburden of the study area is also thick with only one VES curve showed a fresh basement. A warning should be sounded that the presence of clay formations and other building constraints such as fractures, faults and voids may pose serious problem to the building foundations if proper foundation design is not chosen. However, the overall results showed that the site is not suitable for

the proposed high-rise building (guest house). The resistivity values of the subsurface formations indicate that only VES 2 and VES 3 are underlain with fresh basement, the remaining two have fractured basement. This is not enough to rely on for construction of high-rise building.

ACKNOWLEDGEMENTS

The authors appreciate the anonymous reviewers of this manuscript and the editorial board of International Knowledge Press.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Wiki/Saprolite; 2015.
Available: <http://en.wikipedia.org/wiki/saprolite>
2. Ugwu GZ, Ezema PO. 2D electrical resistivity imaging for the investigation of the subsurface structures at the proposed site for Kauridan Estate at Ibagwa – Nike, Southeastern Nigeria. *International Journal of Scientific Research in Knowledge*. 2013;1(12):528-535.
3. Sands TB. Building stability and tree growth in swelling London clay – implication for pile foundation design; 2002.
Available: www.agu.org
4. Ugwu GZ. Electrical resistivity imaging for the investigation of the subsurface formations at Bethel Estate in Emene Industrial Layout, Enugu, southeastern Nigeria. *ASUU-ESUT Jour. Sci. Tech. Human*. 2012;1(1):112-119.
5. Dahlin T, Loke MH. Resolution of 2D Wenner resistivity imaging as assessed by numerical modeling. *J. Appl. Geophys*. 1998;38:237-249.
6. Adagunodo TA, Sunmonu LA. Estimation of overburden thickness of industrial estate Ogbomoso, Southwestern Nigeria. *Advances in Applied Sciences Research*. 2012;3(5):3129-3141.
7. Sunmonu LA, Adagunodo TA, Olafisoye ER, Oladejo OP. The groundwater potential evaluation at industrial estate Ogbomoso Southwestern Nigeria. *RMZ-Materials and Geoenvironmen*. 2012;59(4):363–390.
8. Sunmonu LA, Adagunodo TA, Adeniji AA, Oladejo OP, Alagbe OA. Geoelectric delineation of aquifer pattern in crystalline bedrock. *Open Transactions on Geosciences*. 2015;2(1):1-16.
9. Keary P, Brooks M. An introduction to geophysical exploration. 2nd ed. London; Cambridge University Press. 1991;173-184.
10. Joel ES. Application of geoelectrical resistivity imaging to investigate groundwater potential in Atan, Ogun State Southwestern Nigeria. M.sc. Thesis. Covenant University, Nigeria; 2012.
11. Koefoed O. *Geosounding Principles, 1: Resistivity Sounding measurements*. Elsevier Scientific Publishing Comp., Amsterdam. 1979;275.
12. Griffiths DH, Barker RD. Two dimensional resistivity imaging and modeling in areas of complex geology. *J. Appl. Geophys*. 1993;29: 211-216.
13. Alile, Owens M, Amadasun CVO. Direct current probing of the subsurface earth for water bearing layer in Oredo Local Government Area, Edo State, Nigeria. *Nigeria Journal of Applied Science*. 2008;25:107-116.
14. Loke MH. *Electrical imaging surveys for environmental and engineering studies: A practical guide to 2D and 3D surveys*. 2001;62.
Available: <http://www.geoelectrical.com>
15. Loke MH, Barker RD. Practical techniques for 3D resistivity surveys and data inversion. *Geophys. Prosp*. 1996;44:499-524.
16. Sasaki Y. Resolution of resistivity tomography inferred from numerical simulation. *Geophys. Prosp*. 1982;40:453- 464.
17. Joseph T. Zume, Aondover Tarhule, Scott Christenson. Subsurface imaging of an abandoned solid waste landfill site in Norman Oklahoma. *National Groundwater Association*. 2006;62-69.
18. Vander Velpen BPA. WinRESIST Version 1.0. Resistivity Sounding Interpretation Software. M.Sc. Research Project, ITC, Delft Netherland; 2004.