Integration of geophysically derived parameters in characterization of foundation integrity zones: An AHP approach

S. Bayode, A.A. Akinlalu*, K. Falade, O.E. Oyanameh
Department of Applied Geophysics, Federal University of Technology, Akure, Nigeria

ABSTRACT
An integrated geophysical investigation involving Very Low Frequency Electromagnetic (VLF-EM), and electrical resistivity methods using Schlumberger Vertical Electrical Sounding (VES) techniques was conducted at Deeper Life Camp ground, Ipinsa, Akure, Southwestern Nigeria with the aim of developing a model map that will enhance the knowledge of the subsurface geology viz-a-viz foundation integrity for appropriate location of building within the study area. The effect of four factors including soil apparent resistivity at different depths, depth to bedrock, geology and fracture density on engineering foundation were considered. In order to achieve this, a total of ten traverses were established in approximately NW-SE, NE-SW, N-S and E-W directions with station interval of 5 m and inter-traverse separation of 10 m. One hundred and forty eight (148) station positions were occupied in all for the VLF-EM profiling. Also, fifty four (54) VES stations were occupied across the study area with current electrode spacing (AB/2) varying from 1 to 65 m. Hilbert transform, Amplitude analysis, Fraser technique and Q-Factor performed on the VLF-EM method assisted in the delineation of conductive zones that could be inimical to foundation integrity. The VES result delineated four major geo-electric layers within the study area which are: topsoil, weathered layer, fractured bedrock and the fresh bedrock. The thickness of the layers generally ranges from 0.5-19.6 m. Based on geological and geophysical investigations, foundation integrity map of the area was produced using the Multi-criteria Decision Analysis, approach of Analytical Hierarchy Process (AHP). The model map classified the foundation integrity of the study area into very low, low, moderate, high and very high foundation integrity zones. The competency model at a depth of 3 m is adjudged most suitable for foundation in the study area.

1. Introduction
One of the major problems being faced in the urban areas in Nigeria is the issue of incessant buildings collapse. Statistics of failures of engineering structures such as roads, buildings and bridges throughout the nation has increased geometrically in the last ten (10) years in both sedimentary and Basement Complex areas of the country. Several probable reasons were speculated to have been responsible for this ugly incidence by the engineering community. Adesida and Omosuyi (2005) and Ofomola et al. (2009) have associated these structural defects to improper ways of setting up foundation. In as much as it is desirable to prolong the life of civil engineering structures, it is also important to reduce the loss of lives and properties usually associated with structural failures. It is essential that the site selection for location/erection of engineering foundation is based on competent geological materials. Where such foundation is erected on an unstable earth, structural instability and other forms of defects often set in shortly after the erection of the structure. It is also imperative to know that the hydrogeologic setting of an area will in no small measure have significant impact on the failure of engineering structures (Adesola et al., 2017). The hydrogeologic information are often obtained through the integration of different geophysical techniques as demonstrated in the works of Singh et al.(2019). A conceptual subsoil integrity model map can easily be assessed for selection of foundation site for the erection of safe engineering infrastructures in urban centers. Such foundation integrity maps can be developed by integrating geological and geophysical parameters such as (resistivity, depth to bedrock, lineament/fracture density, lithology etc.) using spatial analysis tool (weighted overlay method) in Multi-Criteria Decision Analysis and Analytical Hierarchy Process (AHP) approach. Authors who have engaged geophysical and geotechnical methods in the investigation of engineering foundation failure includes (Adesida and Omosuyi, 2005; Oladapo et al., 2008; Ofomola et al., 2009; Oyedele et al., 2011; and

* Corresponding author.
E-mail address: aaakinlalu@futa.edu.ng (A.A. Akinlalu).

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Bayode et al., 2012). Preliminary study in the study area shows conspicuous cracks on some existing buildings such as the supermarket, bakery and the Auxiliary Power House (Figures 1 and 2). The buildings show signs of failure (cracks) in various directions and dimensions. Cracks, voids, cavities to mention a few have been delineated using electrical resistivity method particularly the electrical resistivity tomography (ERT) in recent years.

The detection of these features often contributes significantly to engineering site characterization. The neighboring buildings such as the coordinators hostels and the main auditorium around the observed buildings with failure are without cracks. It was also observed that the foundation (basal part) of the buildings that have initiated failure signs along the walls shows evidence of seepages above the ground level.

The geotechnical method of site investigation which can be used to determine the cause of structural failures are traditionally influenced by factors such as shallow depth of investigation, cost ineffectiveness and prolonged time of investigation. Also, geotechnical method has negative impact on the geo-materials and the environment. Thus, relying only on its application may not give the desired results. The geophysical methods rely on measurements of physical properties of the earth material that have significant depth of investigation. It is cost effective, rapid, non-destructive and more environmental friendly than the geotechnical method. Therefore, the application of geophysical methods in the investigation of the subsurface geo-materials of the study area in order to ascertain the cause of the structural failure is necessary. This study is aimed at using GIS based Multi-Criteria Decision Analysis (MCDA) approach and Analytical Hierarchy Process (AHP) to integrate factors influencing engineering integrity derived from soil, geological and geophysical measurements. The integrated approach assisted in classifying the study area into foundation integrity zones.

2. Site description

The study area is the Deeper Life Campground, Akure, Southwestern Nigeria. The study area is situated between geographic coordinates of Northings 809150 and 808700 mN and Eastings 736450 and 736850 mE in the Universal Traverse Mercator (UTM), Minna Zone 31 (Figure 3). The areal extent covered about 2.6 km² built up area.

3. Geology and geotechnical competence

The study area is underlain by the Precambrian Basement Complex rocks of southwestern Nigeria (Rahaman, 1976). The major lithologic unit underlying the study area is predominantly migmatite gneiss (Figure 4). However, further site reconnaissance survey showed evidences of minor intrusion of charnockitic rock in the study area.

The migmatite rock unit, being an older rock, may have undergone intense tectonic deformation and thus more geological structures are observed on it especially when compared with the charnockite rock which rarely fractured. Furthermore, the migmatite gneiss rock often weather into sand and clayey sand soil while charnockite usually weather into clayey soil. Therefore, the geologic conditions of the subsurface suggest that the bedrock of the investigated area is likely to be susceptible to failure by the pressure imposed on it by engineering structures.

4. Methods of study

The Very Low Frequency Electromagnetic (VLF-EM) and electrical resistivity methods with the application of Schlumberger depth sounding technique were employed for this study. Ten traverses were established along NW-SE, NE-SW, W-E and N-S directions with intra station spacing of 5 m (Figure 5). The traverse lengths range from 95 – 125 m. The VLF–EM receiver utilizes the Bordeaux transmitting station with

Figure 1. Cracks at the auxiliary power housing building in the study area.

Figure 2. Other views of cracks on the auxiliary power housing building walls.
frequency range of 15.4–15.8 KHz. Q-factor is the Fraser filtering technique applied to the VLF – EM measurements in this study. It assisted in transforming the anomaly in a way that the inflection points coincide with areas of peak amplitude. In an arrangement of consecutive readings of tilt angle, say Q1, Q2, Q3 and Q4; the term (Q2 – Q1) will not only shifts the dip angle but also reduce the effect of the spatial wavelengths (Adelusi et al., 2014). Numerically averaging weighted values of the adjacent sets of such differences such that (Q3 + Q4) – (Q1 + Q2) reduces the noise level (Adelusi et al., 2014). Where the peak positive Q-factor coincides with the inflection points on the raw real plot is typical of conductive (fractured) zones. The basic principle of this method is best explained in text (Telford et al., 1990; Keary et al., 2004). Karous and Hjelt (1983) filtering method that produces apparent current densities at different depths was performed on the raw real component data, which causes a magnetic field equal to the VLF measurements. The electrical resistivity method adopting the Vertical Electrical Sounding (VES) technique was used for this study. A total of Fifty four (54) VES stations were carried out in the study area (Figure 5). Win Resist version 1.0 software was used for detailed quantitative analysis and 1-D forward modelling. The results are presented as sounding curves, tables and geo-electric sections. For the VES data, the apparent resistivity at electrode spacing (AB) of 4, 6, 8 and 12 m which corresponds to a pre-determined investigation depths of about 1 m, 1.5 m, 2 m and 3 m respectively was used to prepare variation of apparent resistivity maps at these depths for the study area. The depths were determined on the assumption that foundations are usually founded at depth ranging from 0 -3 m. The depth rule adopted rely on the works of Frohlich et al. (1996) and Nejad (2009) which suggested that the maximum exploration depth also known as depth of penetration of the AMNB (AB = Current electrode spacing; MN = Potential electrode Spacing) method is 1/3 to 1/4 of the maximum distance of AB. Depth rule of ½ AB (m) was adopted for this study. This method was adopted to select the pre-determined depth of investigation defined by AB (m) with a view to having a true representative of the apparent resistivity corresponding to a particular depth of investigation which may be quite unrealistic when relying on results from the 1-D forward models performed on apparent resistivity data. A station separation of 5 m was used in other to depict a detail geological structure underlying the study area.

In this research, a GIS-based MCDA concept of Analytical Hierarchy Process (AHP) was adopted to assist in ascertaining the foundation integrity of the buildings to be sited in the study area. This was made possible by.

![Figure 3. Location map of the study area.](image-url)
Identifying parameters that impact effectively on engineering integrity, developing a pairwise comparison matrix through hierarchical model approach, assigning weights to the factors, and performing consistency examination on the pairwise comparison matrix, and rating of parameters using the weighted overlay method. Since the alternative comparison is based on a subjective estimation by the decision maker, it is very vital that it is monitored frequently with a view to securing the required accuracy (Samanta and Mukherjee, 2002).

Obtaining the relative weight is the third phase of the AHP approach. Pairwise matrix are determined for the purpose of normalization and obtaining single eigen vectors, as well as the assigned weight of all the attributes on each hierarchy level \( A_1, A_2, \ldots, A_n \), with a weight vector \( t = (t_1, t_2, \ldots, t_n) \) (Zoran et al., 2011). AHP aggregates various aspects of the decision problem by applying a single optimization function often referred to as the objective function (Saaty, 1994). The goal of AHP is to select the alternative that results in the greatest value of the objective function. In examining the choices, the user applies a numerical scale to compare the choices and the AHP method moves through all pairwise comparisons of criteria and options. The AHP technique thus relies on the assumption that humans usually make relative judgments than absolute judgments. The AHP obtains a weight for each evaluation criterion according to the pairwise comparisons criteria of decision makers; the higher the weight, the more valuable the corresponding criterion. For a fixed criterion, the AHP assigns a point to each alternative according to the output of the pairwise comparisons attributed to the decision maker based on the fixed criterion. The higher the score, the better the performance of the selected alternative with respect to the considered criterion. Conclusively, the AHP integrates the criteria weights and the options points, thus obtaining a global score for each option, and a consequent ranking. The global score for a given option is the summation of the weights of the scores it obtained with respect to all the criteria.

The details of the AHP procedure have been described in the works of Adiat et al. (2012) and Akinlalu et al. (2017). Factors considered are geology, soil apparent resistivity at depths of 1, 1.5, 2 and 3 m, fracture/lineament density and depth to bedrock.

![Geological map of the study area.](image)
Figure 5. Data acquisition map of the study area.

Figure 6. (a) Plot of Q-Factor and Raw Real Component of VLF-EM, (b) Plot of Raw Real component of VLF-EM data, its Hilbert transform and amplitude of analytical signal and (c) K–H pseudo-section of real component data showing the variation of current density along Traverse 1 (W-E Direction).
Figure 7. (a) Plot of Q-Factor and Real component of VLF-EM, (b) Plot of real component of VLF-EM data, its Hilbert transform and amplitude of analytical signal and (c) K-H pseudo-section of real component data showing the variation of current density along Traverse 2 (NW-SE Direction).

Figure 8. (a) Plot of Q-Factor and Raw Real component of VLF-EM, (b) Plot of real component of VLF-EM data, its Hilbert transform and amplitude of analytical signal and (c) K-H pseudo-section of real component data showing the variation of current density along Traverse 3 (NW-SE Direction).
Table 1. Summary of the interpreted VES curves in the study area.

| VES Stations | No of Layers | Resistivity (Ω·m) | Curve Type | Thickness (m) | Depth (m) |
|--------------|--------------|-------------------|------------|---------------|-----------|
| TR1VES1      | 3            | 133, 39, 1508     | H          | 0.6, 2.9      | 0.6, 3.5  |
| TR1VES2      | 3            | 97, 15, 2606      | H          | 0.7, 1.7      | 0.7, 2.4  |
| TR1VES3      | 3            | 300, 736, 1468    | A          | 0.7, 5.3      | 0.7, 6.0  |
| TR1VES4      | 5            | 271, 579, 52, 779, 8919 | KHA | 0.5, 1.8, 1.3, 0.9 | 0.5, 2.3, 3.6, 4.5 |
| TR1VES5      | 3            | 36, 697, 2784     | A          | 0.8, 3.3      | 0.8, 4.1  |
| TR1VES6      | 3            | 35, 358, 2885     | A          | 2.3, 3.1      | 2.3, 3.4  |
| TR1VES7      | 3            | 33, 125, 292      | A          | 1.5, 6.0      | 1.5, 7.5  |
| TR2VES8      | 3            | 130, 27, 118      | H          | 0.7, 12.9     | 0.7, 13.6 |
| TR2VES9      | 3            | 51, 402, 1723     | A          | 0.8, 5.0      | 0.8, 5.7  |
| TR2VES10     | 3            | 106, 252, 655     | A          | 1.3, 3.5      | 1.3, 4.8  |
| TR2VES11     | 3            | 80, 504, 777      | A          | 0.9, 5.0      | 0.9, 5.9  |
| TR3VES12     | 3            | 87, 154, 740      | A          | 0.5, 3.6      | 0.5, 4.2  |
| TR3VES13     | 3            | 125, 168, 767     | A          | 0.9, 3.6      | 0.9, 4.5  |
| TR3VES14     | 4            | 660, 69, 628, 1820 | HA | 0.5, 4.9, 7.2 | 0.5, 5.4, 12.7 |
| TR3VES15     | 3            | 78, 27, 2034      | H          | 0.9, 4.3      | 0.9, 5.3  |
| TR3VES16     | 3            | 49, 146, 914      | A          | 1.5, 14.8     | 1.5, 16.3 |
| TR3VES17     | 3            | 150, 14, 2954     | H          | 0.4, 1.8      | 0.4, 2.2  |
| TR4VES18     | 4            | 159, 188, 64, 5264 | KH | 0.8, 3.0, 1.8 | 0.8, 3.8, 5.6 |
| TR4VES19     | 3            | 80, 139, 1975     | A          | 1.2, 3.4      | 1.2, 4.6  |
| TR4VES20     | 3            | 47, 94, 1437      | A          | 1.2, 6.6      | 1.2, 7.7  |
| TR4VES21     | 3            | 46, 71, 2410      | A          | 1.8, 2.0      | 1.8, 3.8  |
| TR4VES22     | 3            | 210, 38, 1195     | H          | 0.7, 4.2      | 0.7, 5.0  |

(continued on next page)
| VES Stations | No of Layers | Resistivity (Ω-m) | Curve Type | Thickness | Depth (m) |
|--------------|--------------|------------------|------------|-----------|-----------|
| TR4VES23     | 3            | 34, 75, 507      | A          | 1.5, 5.8  | 1.5, 7.3  |
| TR5VES24     | 3            | 127, 81, 1644    | H          | 1.3, 2.2  | 1.3, 3.5  |
| TR5VES25     | 3            | 71, 203, 6477    | A          | 2.5, 2.4  | 2.5, 4.9  |
| TR5VES26     | 3            | 166, 97, 4495    | H          | 1.0, 5.3  | 1.0, 6.3  |
| TR5VES27     | 4            | 128, 25, 852, 3316| HA         | 0.5, 1.0, 2.0 | 0.5, 1.4, 3.4 |
| TR6VES28     | 3            | 74, 65, 3665     | A          | 0.8, 3.4  | 0.8, 4.2  |
| TR6VES29     | 3            | 49, 896, 80621   | A          | 1.7, 0.6  | 1.7, 2.3  |
| TR6VES30     | 3            | 145, 53, 2146    | H          | 0.6, 2.0  | 0.6, 2.6  |
| TR6VES31     | 4            | 143, 46, 681, 1974| HA         | 0.6, 1.6, 11.2 | 0.6, 2.2, 13.4 |
| TR6VES32     | 3            | 192, 128, 1220   | H          | 0.9, 2.6  | 0.9, 3.5  |
| TR7VES33     | 3            | 20, 169, 1089    | A          | 1.7, 1.3  | 1.7, 3.0  |
| TR7VES34     | 3            | 61, 26, 1412     | H          | 0.7, 3.3  | 0.7, 4.0  |
| TR7VES35     | 3            | 96, 179, 376     | A          | 6.4, 4.0  | 6.4, 10.4 |
| TR7VES36     | 3            | 61, 122, 11971   | A          | 1.4, 7.6  | 1.4, 9.0  |
| TR7VES37     | 4            | 55, 140, 114, 4671| KH         | 2.1, 3.8, 9.5 | 2.1, 5.9, 15.5 |
| TR7VES38     | 3            | 26, 43, 1186     | A          | 1.4, 4.4  | 1.4, 5.8  |
| TR8VES39     | 3            | 52, 55, 2390     | A          | 1.1, 1.4  | 1.1, 2.6  |
| TR8VES40     | 3            | 127, 88, 368     | H          | 2.2, 10.8 | 2.2, 13.1 |
| TR8VES41     | 3            | 50, 681, 720     | A          | 0.9, 10.6 | 0.9, 11.5 |
| TR8VES42     | 3            | 108, 46, 907     | H          | 0.7, 7.9  | 0.7, 8.6  |
| TR8VES43     | 3            | 96, 37, 830      | H          | 1.0, 5.8  | 1.0, 6.8  |
| TR8VES44     | 3            | 62, 25, 524      | H          | 0.9, 7.2  | 0.9, 8.1  |

(continued on next page)
5. Results and discussion

5.1. Fracture delineation from VLF-EM method

The VLF-EM measurements along Traverses 1, 2 and 3 are presented as profiles and 2-D subsurface images (Figures. 6a, b; 7a, b; 8a, b). Delineation of fractures from VLF-EM method involves the plots of Q-factor, raw real and amplitude response components against distance along traverses 1–3 (Figures. 6a, b; 7a, b; 8a, b). Where the inflection points of raw real component coincide with the positive peak amplitude of the Q-factor/Hilbert transform plot is typical of suspected basement fracture (conductive) zones (Afolayan et al., 2004). The yellowish–reddish colour bands in the 2-D image are also indicative of the presence of conductive zones within the subsurface.

Conductive zones were delineated along Traverses 1–3 using the various filtering techniques. The Q-Factor (Figures 6a; 7a; 8a) identified conductive zones occurring at distances 45 m and 75 m; 15 m, 35 m and 60 m; 13 m and 100 m respectively along Traverses 1–3. The Amplitude Analytical Signal (AAS) technique (Figures 6b; 7b; 8b) were used to identify conductive zones occurring at distances 35 m, 55 m, and 70 m; 20 m, 30 m, 85 m and 100 m; 10 m, 45 m, 86 m and 110 m marked CZ1, CZ2, and CZ9, CZ4, CZ6, CZ9, CZ6, and CZ7, and CZ4, CZ6, CZ10, and CZ11 respectively along Traverses 1–3. Also from the 2-D images (Figures 6c; 7c; 8c), weakly conductive zones (yellowish colour band) were delineated at distances 10 m, 45 m and 80 m; 25 m and 65 m; 10 m, 45 m, 86 m and 110 m respectively along Traverses 1–3.

5.2. Vertical Electrical Sounding results

The results of VES interpretation are presented as sounding curves, tables and maps.

5.3. Classification of VES curves

A summary of the fifty four (54) Vertical Electrical sounding (VES) interpretation results are presented in Table 1. Five type curves namely A, H, K, KH and KHA were obtained from the investigated area (Figure 9). This suggests, among other things, three possible subsurface layer situations (Adiat et al., 2017). The first situation is such that the study area is dominated by the presence of fresh basement at a very shallow depth directly underneath the topsoil as seen in the A and K curves observed in the third geoelectric layer in (Figure 9). Secondly, some sections of the studied area are typical of a three layer case with the second layer interpreted to be the weathered basement layer as typified by the H type curve. This can also have a negative impact by decreasing the strength of the foundation thereby subjecting it to rapid failure, particularly if the depth to the water table in the weathered layer is shallow. Also, the foundation integrity is compromised if the weathered layer material is highly conductive. The third situation describes the delineation of fractured zone within the basement as observed in the third geoelectric layer (Adiat et al., 2017). The presence of fractured basement often plays significant roles in undermining the integrity of any engineering structure sited on such geological features in the study area.

5.4. Factors influencing foundation integrity

5.4.1. Soil apparent resistivity (Rt)

The soil apparent resistivity is an important factor that gives vital information about the nature of the subsurface materials and their effect on foundation integrity. The apparent resistivity at depths of 1 m, 1.5 m, 2 m and 3 m were considered in evaluating the nature of the subsoil and its foundation integrity around the study location. Figure 10 shows the map of apparent resistivity values at depth of 1 m in the study area. The values generally range from 14 – 735 Ω-m and
structures. The very low to low resistivity zones range in value from 14 – 181 Ω-m and 515 – 682 Ω-m respectively are classified as sand, laterite and fresh basement bedrock layer respectively and thus considered to be competent to withstand high-rise building foundation load that will stand the test of time. This suggests that the area around the youth hall is relatively safe for erection of engineering structure. Figure 11 presents the map of apparent resistivity values at a depth of 1.5 m. The apparent resistivity values generally ranges from 14 – 849 Ω-m and displayed similar scenario and classification as observed in the apparent resistivity values at depth of 1 m (Figures 10 and 11). Relatively competent zones for foundation integrity displaying moderate to very high apparent resistivity values of 515–682 Ω-m and 682–849 Ω-m are observed in the central part and extends to the area around the youth hall in the study area. It should be noted however, that the area surrounding these zones are characterized by relatively very low, low and moderate apparent resistivity values which range from 14 – 181 Ω-m, 181–348 Ω-m and 348–515 Ω-m respectively and hence suggests area that are susceptible to foundation failure due to its low apparent resistivity value at that depth (Figure 11).

Figure 12 reveals the apparent resistivity image at a depth of 2 m. The resistivity values generally range from 25 – 80,000 Ω-m. The very low to low apparent resistivity (25–336 and 336–356) ohm-m zones dominate the west, northern and eastern parts of the study area (Figure 12). This indicates that engineering structures located in the area will be standing on an incompetent near surface subsoil at this depth range. However, moderate to very high apparent resistivity (366–542, 542–717 and 717–893) ohm-m zones respectively are indicative of relatively competent subsurface materials observed in the central and towards the southern part of the study area. These areas are characterized with pockets of low apparent resistivity zones (Figure 12).

Figure 13 is the map showing the apparent resistivity values corresponding to an approximate depth of 3 m. The apparent resistivity values generally range from 25 – 80,000 Ω-m. The very low to low apparent resistivity (25–336 and 336–356) ohm-m zones are typical of clayey and sandy clay materials and could compromise the foundation of existing and proposed building at these locations. These zones are obvious in the western and north eastern part of the study area depicted by green colour band (Figure 13). Moderate apparent resistivity values and high to very high resistivity zones (356–667, 667–5501 and 5501–80618) ohm-m typical of clayey sand, sand/laterite and fresh basement bedrock were observed in the north central, central, south and towards the south eastern part of the study area respectively. Very high competent zones are observed at the extreme southern part of the study area. These observations suggest that at the depth of about 3 m, more areas within the study area become more competent. These high competence zones favour higher integrity of the proposed or existing foundation at these locations.

5.4.2. Depth to bedrock

The composite depth to bedrock map (Figure 14) was generated from the depths to rock head obtained from the VES points. The basement topography which is dependent on the overburden thickness also plays a vital role in subsoil stability. Areas that are characterized with thin overburden resulting to shallow depth to bedrock, possess better stability potential provided the bedrock is devoid of geological structures (fractures) or susceptible to extreme weathering activities. In (Figure 14), the depth to bedrock generally ranges from 2.3 – 16.6 m. It is observed that the zones located in the south, southeastern and north-central parts of the study area are considered to be geotechnically competent due to the relatively thin overburden thickness (2.5–5.2 m) observed in the area (Figure 14). On the other hand, zones found in the western axis and some pockets in the north eastern part of the study area have higher overburden thickness values (10.6–13.7 m and 13.7–16.6 m) (Figure 14). These zones may pose a threat related to differential settlement to civil engineering structure if the foundation of such building spanned over thin and thick overburden zones.
The depth to bedrock map is however, considered an important factor in developing a conceptual model map for engineering foundation integrity in the study area.

5.4.3. Fracture/lineament density map

Lineaments are surface manifestations of structurally controlled subsurface features such as fractures (Akinlalu et al., 2017). The higher the lineament density, the less competent the subsoil is, and the more susceptible the foundation to failure. Figure 15 shows the lineament density map of the study area. The map suggests that the west, northern, northeastern and a small portion in the southeastern parts of the study area are observed to be characterized with denser lineament values (13.5–27.1/Km, 27.1–40/Km and 40.0–54.2/Km) and are considered to be incompetent (Figure 15). However, the south, southeastern around the youth hall, north-central and a small pockets in the western part of the study area displayed very low lineament density values (0–13.5/Km) and are thus envisaged to be more competent to withstand the foundation of an existing/proposed engineering structure (Figure 15).

5.4.4. Geology

The geology of the study area is as earlier presented in Figure 4. Geologically, migmatite-gneiss and charnockite rock units were observed to underlain the study area (Figure 4), Charnockite rock which weather quickly to clay is given lower preference in determining its engineering integrity. The subsoil in the area dominated by migmatite-gneiss rock unit, contain more sand fraction and hence, is expected to be more relatively stable geologically to support foundation and other engineering structures than the charnockite dominated area.

5.5. Consistency examination of the constructed pairwise comparison matrix

Table 2 shows the Satty scale for weight assignment and its interpretation while Tables 3 and 4 contains the pairwise comparison matrix and the factor weights. However, the consistency ratio equals 0.08 and since 0.08 < 0.1, it implies that the estimated weights of 0.1896, 0.0595, 0.5727 and 0.1782 with respective percentages of 18.96 %, 5.95 %, 57.27 6% and 17.82 % is reliable for this study.
5.6. Classification and rating of factors

Rating scale of 1–5 was adopted for this study. Each parameter was scored on 1–5 scale in ascending order of engineering significance. It is important to state that the resistivity range of any given rock type is wide and overlaps with other rock types (Keary et al., 2004). Therefore, different types of lithology may have same resistivity values.

The prevailing geological conditions and fracture/lineament density disposition of the area as well as the results of similar works from similar geological environment reported in literatures were used as guides to obtain the classifications and ratings shown in Table 5.

5.7. Foundation integrity index estimation

5.7.1. Conceptual model of engineering foundation integrity

Based on the generated thematic maps and their numeric range ranking and classification, the foundation integrity conceptual model map of the area was generated based on the selected factors contributing to the integrity of the foundation at depths 1 m, 1.5 m, 2 m and 3 m (Figures 16, 17, and 18). Spatial Analysis tool (weighted overlay method) in Multi-criteria Decision Analysis approach of Analytical Hierarchy Process (AHP) was adopted. The conceptual model maps generated show that the study area can be classified generally into very low, low, moderate, high and very high foundation integrity zones.

Figure 16 shows the competency map where apparent resistivity corresponding to a depth of 1 m was used for the model development. The model classified the study location into Very low, low, moderate and high foundation integrity zones. Very low to low integrity zones dominate the study area at 1 m depth; thereby, suggesting subsoil incompetence for foundation at that depth (Figure 16). However, moderate to high integrity zones were observed in a small area closed to the youth hall (Figure 16). This observation showed that any foundation proposed for the study area at a depth of <1 m is safe within the zones classified as moderate to high foundation integrity zones.

Figure 17 reveals the foundation integrity model map corresponding to a depth of 1.5 m. The model map classified the study area into very low to low and moderate foundation integrity zones. The western and southern flank of the study area is predominantly characterized by very
low foundation integrity zone, with low integrity zones dominating the central and eastern part of the studied locations (Figure 17). Pockets of moderate foundation integrity zones were observed in the central and around the youth center, thus suggesting that at a depth of 1.5 m, subsoil foundation integrity is very poor/poor in the study location.

Figure 18 shows the integrity/competency model map at a depth of 2 m. The model map at this depth classified the study area into very low, low and moderate foundation integrity zones. The area is predominantly very low to low foundation integrity at this depth (Figure 18). Only a small portion of the study area in the central and southeastern parts of the investigated area exhibits moderate competence properties. These observations generally imply that foundation integrity at depth of about 2 m in the study area is also very poor (Figure 18).

Figure 19 is the foundation integrity model map corresponding to a depth of 3 m in the study area. The model map classified the study area into very low, low, moderate, high and very high competence zones. The very low and low integrity zones dominate the western and north eastern part of the study area (Figure 19). The central part of the study area is predominantly characterized by moderate integrity zones with pockets of high competency zones. The high foundation integrity zones were observed in the southeastern part with small pockets in the central part of the investigated area (Figure 19) while the very high foundation integrity zone is located in a small area in the southeastern part of the study area. This model map suggests that, proposed high structures in the study area should be concentrated around the central and southern part of the study area due to its greater stability/higher subsoil foundation integrity. This is probably responsible for the stability of the existing building foundation around the youth hall in the study area.

Generally, visual inspection showed that buildings around the uncompleted hostel and existing hostel blocks are already showing evidence of cracks, whereas there is no evidence of cracks observed in existing buildings around the youth hall. These assertions corroborate the integrity competence model map which suggests that the area around the Youth hall is standing on a moderately competent zone, thus confirming the reliability of the model subsoil integrity map developed for the investigated area.
Figure 13. Soil Apparent Resistivity (Ωm) Map at 3 m depth in the Study Area.
Figure 14. Depth to bedrock map of the study area.
Figure 15. Fracture/lineament density map of the study area.

Table 2. Saaty’s scale for assignment of weight (Satty, 1980).

| Less Important | Equally Important | More Important |
|----------------|-------------------|----------------|
| Extremely      | Very Strongly     | Strongly       |
| 1/9            | 1/7               | 1/5            |
| 1/3            | 1                 | 3              |
| 1              | 5                 | 7              |
| 9              | 16                | 5.3            |

Table 3. Pairwise comparison matrix table for foundation integrity indices.

|     | Ld | Db | Rt | Ge |
|-----|----|----|----|----|
| Ld  | 1  | 5  | 1/5| 1  |
| Db  | 1/5| 1  | 1/7| 1/3|
| Rt  | 7  | 1  | 1/3| 1  |
| Ge  | 1  | 3  | 1  | 5.3|
| Sum | 7.2| 16 | 1.7| 5.3|

Ld = Lineament Density; Db = Drainage Density; Rt = Resistivity; Ge = Geology.

Table 4. Determination of relative weights for foundation integrity indices.

|     | Ld | Db  | Rt   | Ge  | Weights |
|-----|----|-----|------|-----|---------|
| Ld  | 5/36| 5/16| 21/176| 3/16| 0.1896  |
| Db  | 1/36| 1/16| 15/176| 1/16| 0.0595  |
| Rt  | 25/36| 7/16| 105/176| 9/16| 0.5727  |
| Ge  | 5/36| 3/16| 35/176| 3/16| 0.1782  |
| Sum | 1   | 1   | 1    | 1   | 1       |

Ld = Lineament Density; Db = Drainage Density; Rt = Resistivity; Ge = Geology.
### Table 5. Ratings for the foundation integrity parameters.

| Factors                        | Category (Classes)   | Potentiality for Engineering Development | Rating | Normalized Weight |
|--------------------------------|----------------------|------------------------------------------|--------|-------------------|
| Soil Apparent Resistivity (Rt) at (1m, 1.5m, 2 m & 3m) | 4-159                | Very Low                                 | 1      | 0.5727 (57.27%)   |
|                                | 159-303              | Low                                      | 2      |                   |
|                                | 303-447              | Moderate                                 | 3      |                   |
|                                | 447-591              | High                                     | 4      |                   |
|                                | 591-735              | Very High                                | 5      |                   |
| Depth to Bedrock (Db)          | 2.30-5.15            | Very High                                | 5      | 0.0595 (5.95%)    |
|                                | 5.15-8.00            | High                                     | 4      |                   |
|                                | 8.00-10.85           | Moderate                                 | 3      |                   |
|                                | 10.85-13.70          | Low                                      | 2      |                   |
|                                | 13.70-16.56          | Very Low                                 | 1      |                   |
| Fracture/Lineament density (Ld) | 0.00-13.54           | Very Low                                 | 1      | 0.1896 (18.96%)   |
|                                | 13.54-27.08          | Low                                      | 2      |                   |
|                                | 27.08-40.62          | Moderate                                 | 3      |                   |
|                                | 40.62-54.16          | High                                     | 4      |                   |
|                                | >54.16               | Very High                                | 5      |                   |
| Geology (Ge)                   | Charnockite          | Very Low                                 | 1      | 0.1782 (17.82%)   |
|                                | Migmatite Gneiss     | Moderate                                 | 3      |                   |

Rt = Soil Apparent Resistivity.

**Figure 16.** Foundation integrity model map at 1 m depth.
Figure 17. Foundation integrity model map at 1.5 m depth.
Figure 18. Foundation integrity model map at 2.0 m depth.
6. Conclusion

An integrated geophysical survey was carried out at Deeper Life Camp ground, Ipinsa, southwestern Nigeria with a view to enhancing the knowledge of the near subsurface integrity of the area for engineering structures. Factors such as apparent resistivity, lineament density, Geology and depth to bed rock were identified as the major contributing factors to foundation integrity in the study area. Areas with moderate to high resistivity were considered as competent zones for foundation in the study area. Areas devoid of lineaments or with minimal lineament density are concluded to be suitable for foundation. The nature of the subsurface material as well as the depth to competent bed rock in the studied locations played significant roles in the development of foundation integrity map for the study area. The Analytical Hierarchy Process (AHP) assisted in assigning weights to the contributing factors. The study concluded that Resistivity of the subsoil, lineament density, geology and depth to bedrock contributes 57%, 6%, 19% and 18% respectively to foundation integrity in a typical basement complex environment like the study area. These factors were used to develop four thematic maps which are used to classify the study area into Very low, low, moderate, high and very high foundation integrity zones. The developed foundation integrity maps showed very poor foundation properties at depths of 1 m, 1.5 m and 2 m. Moderate to very high competency/foundation integrity zones were observed in major part of the investigated area at a depth 3 m in the central and southern part of the study area. These observations suggest that several precautions need to be put into consideration before erecting buildings in the area. This is supported by observed cracks which are conspicuously evident on the existing hostel and uncompleted hostel blocks erected in the area.

Figure 19. Foundation integrity model map at 3.0 m depth.
Declarations

Author contribution statement

Bayode S.: conceived and designed the experiments; analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the paper.

Akinlalu A. A.: performed the experiments; analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the paper.

Falade, K.: conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; contributed reagents, materials, analysis tools or data.

Oyanameh, O. E.: performed the experiments; analyzed and interpreted the data; wrote the paper.

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References

Adelusi, A.O., Ayuk, M.A., Kayode, J.S., 2014. VLF-EM and VES: an approach to groundwater exploration in a Precambrian basement terrain SW Nigeria. Ann. Geophys. 57 (1), 1–11.

Adesida, A., Omouny, G.O., 2005. Electrical resistivity survey around the mini campus of the federal university of technology, Akure, southwestern Nigeria and geotechnical significance. Niger. J. Pure Appl. Phys. (NJPAP) 4 (2), 211–234.

Adiat, K.A.N., Akinlalu, A.A., Adegboyere, A.A., 2017. Evaluation of road failure vulnerability section through integrated geophysical and geotechnical studies. NRIAG J. Astron. Geophys. 6, 244–255, 2017.

Adiat, K.A.N., Nawawi, M.N.M., Abdullah, K., 2012. Integration of geographic information system and 2D imaging to investigate the effects of subsurface conditions on flood occurrence. Canadian Journal of Science and Education 6 (3), 11–21.

Adeluyi, J.F., Olorunfunmi, M.O., Afolabi, O., 2004. Geo-electric/electromagnetic VLF survey for groundwater development in a basement Terrain-A case study. Ife J. Sci. 6 (1), 74–78.

Akinlalu, A.A., Adegboyi, A., Adiat, K.A.N., Akeredolu, B.E., Lateef, W.Y., 2017. Application of multi-criteria decision analysis in prediction of groundwater resources potential: a case of Oke-ana, Ile-ana area, southwestern, Nigeria. NRIAG J. Astron. Geophys. 6, 182–200, 2017.

Adeola, Omosuyi, G.O., Adelusi, A.O., 2017. Integrated geophysical investigation for pavement failure along a dual carriage way, Southwestern Nigeria: a case study. Kuwait J. Sci. 44 (4), 135–149.

Bayode, S., Omosuyi, G.O., Abdullahi, H.I., 2012. Post-foundation engineering geophysical investigation in part of the federal university of technology, Akure, southwestern Nigeria. J. Emerg. Trends Eng. Appl. Sci. 3 (1), 203–210.

Frohlich, R.K., Fisher, J.J., Summerle, E., 1996. Electric-hydraulic conductivity correlation in fractured crystalline bedrock: central landfield, Rhode Island, USA. J. Appl. Geophys. 35, 249–259.

Karoun, M., Hjejle, S.E., 1983. Linear filtering of VLF dip-angle measurements. Geophys. Prospect. 31, 782–794.

Keary, P., Brooks, M., Hill, I., 2004. In: An Introduction to Geophysical Exploration, third ed. Blackwell Science, Oxford, p. 262pp.

Nejad, M.T., 2009. Geo-electric investigation of the aquifer characteristics and groundwater potential in bebahahan araz university farm, Khuzestan province, Iran. J. Appl. Sci. 9 (20), 3691–3698.

Ofomola, M.O., Adiat, K.A.N., Oluyanj, G.M., Ako, B.D., 2009. Integrated geophysical methods for post foundation studies, Obanla staff quarters of the federal university of technology, akure, Nigeria. J. Sci. Technol. 10 (2), 93–111.

Oladapo, M.I., Olorunfemi, M.O., Ojo, J.S., 2008. Geophysical investigation of road failures in the basement complex areas of southwestern Nigeria. Res. J. Appl. Sci. 3 (2), 103–112.

Oyesile, K.F., Oladele, S., Adegboyere, O.J., 2011. Application of geophysical and geotechnical methods to site characterization for construction purposes at Ikoyi, Lagos, Nigeria. J. Earth Sci. Geotech. Eng. 1 (1), 87–100.

Rahaman, M.A., 1976. Review of the basement geology of south-western Nigerian. In: Public, commercial, or not-for-profit sectors.

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Adesida, A., Omosuyi, G.O., 2005. Electrical resistivity survey around the mini campus of the federal university of technology, akure, southwestern Nigeria and geotechnical significance. Niger. J. Pure Appl. Phys. (NJPAP) 4 (2), 211–234.