

RESEARCH ARTICLE

PRE- FOUNDATION STUDIES USING VERTICAL ELECTRICAL SOUNDING AND SOIL SAMPLE ANALYSIS

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ABSTRACT

Subsurface rock properties investigation to categories foundation competent layer for the proposed engineered structure capable of housing offices, lecture halls, and laboratories was carried out using geophysical (GPHY) and geotechnical (GTECH) techniques. Electrical resistivity GPHY technique using vertical electrical sounding (VES) field procedure was utilized in which nineteen (19) VES spots were occupied. Results of the VES revealed 2-D subsurface geoelectric sequences comprising of incompetent overburden layer of about 5 m thick with resistivity value between 10 and 210 ohm-m typical of clay soil material. Beneath this layer are sand formation and fresh bedrock with resistivity range of 750 to 1000 ohm-m, which are good formations for foundation. Additionally, according to GPHY studies, western and northern portions of the region are marked by fractures/faults, which could cause building subsidence if foundation is stationed at these points. The results of the analyses of the soil samples taken in five different points in the study area revealed: (1) grain size distribution with 0.075 mm particle size passing of an average of 41% signifying the occurrence of clay, corroborating the presence of clay material within the weathered layer in GPHY investigations; (2) active and expansive nature of the soil with linear shrinkage greater than 8% revealing unsuitability of topsoil for foundation; (3) medium plasticity of soil indicating possible soil swelling; and (4) concomitant GTECH and GPHY results of the topsoil and weathered layer properties. The overburden layer with clayey materials must be removed and areas with geological structures must be taken into account.

KEYWORDS

Vertical Electrical Sounding, Conductivity, Foundation, Geotechnical, Subsidence

1. INTRODUCTION

Developed countries use GPHY and GTECT site investigation as a benchmark before beginning the design phase of engineering projects. According to (Oyeniran and Falae, 2018), this routine procedure aims to reduce construction failure by determining the geological conditions and the ability of the underlying soil formations to withstand the load capacity of the structure. Such practices are not prioritized in the developing countries, such as Nigeria, consequently leading to structural defects and a string of building collapses (Oyedele, 2011). A foundation is important parts of engineering structures that support the weight of the structure and transfers it to the soil underneath it. However, when the subsurface soil materials are geologically deformed and/or lack requisite GTECT properties, construction problems may arise with an outcome of structural defect (Soupois 2007, Oyedele et al., 2011, Adeoti et al., 2016, Olayanju et al., 2017). Investigations of vital parameters (subsurface soil qualities and geologic conditions) to be considered before designing an engineering structure have been demonstrated by (Bremmer, 1999, Omoyoloye, et al., 2008, Arora, 2008, Nwankwoala and Warmate, 2014). Natural phenomena, which include natural activity like earthquakes, tremors, and faulting are one of the reasons for engineering structural failures/defects in addition to poor pre-investigation (Oyedele, 2009, Aghamelu, 2011, Khatri, 2011, Olorode, et al. 2012, Cardarelli, 2018). Earthquakes and tremor are significantly manifested in an area where faulting is enormous. In such an area, GPHY investigation can be used to delineate fault and fracture system to facilitate pre design of

engineering structure. Detecting the existence of geological structure such as fracture system and its spatial continuity in the subsurface is however, a major drawback for GTECT investigation. These constraints require the combination of GPHY and GTECT to totally exploit the subsurface conditions.

Engineering GPHY deals with the unraveling of engineering performance of earth materials (soil and rock) as related to foundations of roads, railway lines, buildings, tunnels, and power plants using appropriate GPHY prospecting techniques. Foundation investigation methods such as boring, drilling, pitting and trenching are very costly, invasive, and time-consuming unlike engineering GPHY method which provides less laborious and cost-effective alternative with accurate results without disturbance of the earth materials (Olorunfemi, et al, 2002; Akintorinwa and Adesoji, 2009; Akintorinwa and Adeusi, 2009; Ofomola et al., 2009). Frequently used GPHY methods in engineering GPHY survey include Electromagnetic (EM), Electrical and Seismic Refraction (Reynolds, 2011; Rungroj, 2015; Bharti, et al., 2016; Fajana, et al., 2016; Das, et al., 2017; Pazzi, et al., 2018; Bharti, et al., 2019; Singh, et al., 2019; Gupta et al., 2020). These methods exploit the science of natural phenomenon of the earth to assess the physical properties of the subsurface (Olaleye, et al., 2020), by revealing depth to bedrock, the presence of geologic structures, and the competency of subsurface (Guptal, et al., 2018; Srivastava, 2020). On the other hand, the GTECT investigation involves subsurface GTECT evaluation such as Natural Moisture Content, Particle Size Analysis, Atterberg Limits comprising liquid limit (LL) and plastic limit (PL). While Linear Shrinkage, Compaction Test, and Unconfined Compression are

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further GTECH metrics that aid the determination of the soil's competency (Bharti et al., 2016).

Pre-foundation studies were conducted in the Study Area using both GPHY and GTECH technique as a result of expansion drive of an Institution management. The proposed structure is to host offices, laboratories, and lecture rooms. The research's findings will establish (1) the capacity of subsoil materials to support the foundation of the structures (2) the potential depth at which the foundation could be positioned (3) prevent economic loss that could accompany future structural failure and, (4) the need for pre-foundation studies as a precautionary measure to prevent widespread building collapse in the nation.

2. GEOLOGICAL SETTING

Geology of the research area has been described in detail by (Rahman, 1989). Biotite granite and gneiss migmatite are the primary geological features in the region.

3. MATERIALS AND METHODOLOGY

3.1 Electrical Resistivity Survey

GPHY method engaged in the studied area was electrical resistivity GPHY survey with the aid of R-50 resistivity meter. With the use of a Schlumberger array and electrode spacing (AB/2) of up to 65 m, 19 VES

data were collected in order to map the distribution of the subsurface apparent resistivity (A_RESIST). To determine the type of depth sounding curves, observed A_RESIST (Ω m) values were plotted against electrode spacing AB/2 (m). A qualitative assessment involving visual evaluation of the sounding curves was conducted in an effort to gain first-hand knowledge of the subsurface structure of the research area. In order to establish geoelectric parameters for each location within the study region, the sounding curves were additionally subjected to curve matching using conventional electrical resistivity master and auxiliary curves. Geoelectric parameters are dependable clue of soil competence classification (Olorunfemi et al., 2004). The result of the iteration was then presented as geoelectric sections and maps. These were subsequently used to quantitatively evaluate the resistivity and thickness of the subsurface layers (Olorunfemi et al., 2004) (Table 1).

3.2 Geotechnical Investigation

Five (5) soil samples were collected at a depth approximately 1m in the study area (Figure 1). The samples were adequately tagged and taken to the laboratory for the following geotechnical test; natural moisture content, particle size analysis, Atterberg limits test (Liquid Limit, Plastic Limit), linear shrinkage, unconfined compression, and compaction test. These tests were carried out in accordance with global best practices utilizing (BSI, 1990) as a reference point. Presentations of the geotechnical data include graphs, charts, curves, and tables.

Table 1: Competence Rating of Lithology Based on A_RESIST Values (Olorunfemi et al., 2004)

A_RESIST range ohm-m	Lithology	Competence rating
<100	Clay	Incompetent
100 - 300	Sandy Clay	Moderate Competent
300 - 750	Clayey Sand	Competent
>750	Sand	Highly Competent

4. RESULTS AND DISCUSSION

4.1. Electrical Resistivity

Four (4) sounding curve types: A, KH, H, and HKA; identified from the geoelectric curves of the study area; and Table 2 shows the result of the geoelectric parameters. A maximum of five (5) subsurface layers with reliable indications of soil competency were identified based on the geoelectric parameters classifications (Table 2). The delineated subsurface layers include topsoil, weathered layer, partly weathered/fractured bedrock, faulted basement, and fresh basement (bedrock). Generally, topsoil is an incompetent soil layer for foundation emplacement because it is expected to be dug out, therefore, emphasis are laid on the subsequent layers beneath the topsoil for soil competent

investigations. Depending on the resistivity range of the weathered layer, some are considered competent. From Table 1, clay have flow propensity under stress, render the soil material incompetent as they cause differential displacement on building walls (Sheriff, 1991). On the other hand, sand, clayey sand, and crystalline rocks (bedrock) are competent subsurface materials due to their ability to hold on to stress (Sheriff, 1991; Olorunfemi et al., 2002). Due to the significant depth of occurrence, VES analysis at the third layer mostly indicates compacted soil at depth of about 2 to 5 m. However, the third layer of VES 5 and 10, and the fourth layer of VES 14 (Table 2) have a resistivity classification of loose soil, an indication of a fractured/faulted filled with clayey sand or sandy clay materials, therefore rendering the VES locations unsuitable for the deployment of foundations. Overburden layer is a term used to describe the weathered, topsoil and clay incompetent layers.

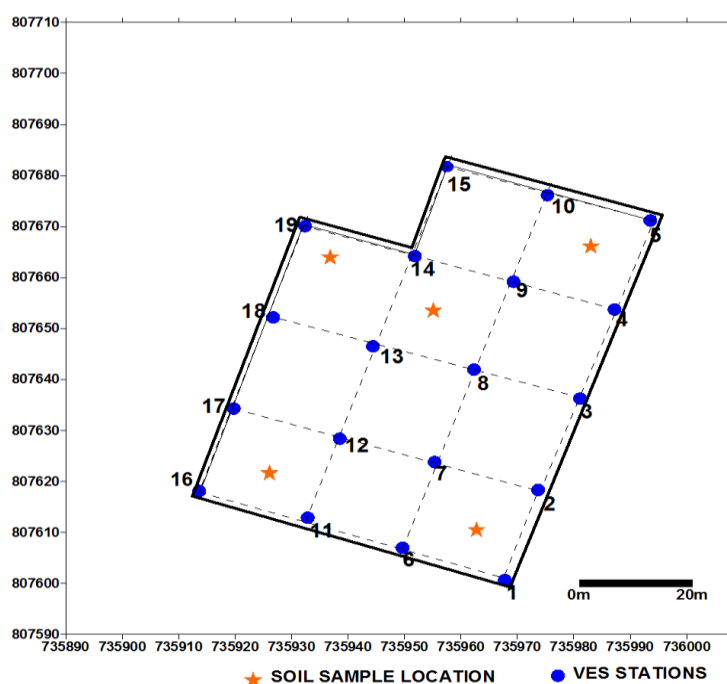


Figure 1: Study area map showing VES stations and soil sample locations.

Table 2: Geoelectric Parameters of Interpreted VES

VES	$\rho_1(\Omega m)$	$\rho_2(\Omega m)$	$\rho_3(\Omega m)$	$\rho_4(\Omega m)$	$\rho_5(\Omega m)$	$h_1(m)$	$h_2(m)$	$h_3(m)$	$h_4(m)$	CURVE TYPE
1	461	178	833	—	—	1.5	4.9	—	—	H
2	332	41	1958	—	—	1.4	2.0	—	—	H
3	199	43	505	—	—	1.0	4.1	—	—	H
4	635	10	1805	—	—	2.2	1.1	—	—	H
5	290	835	81	1548	—	1.1	2.4	8.7	—	KH
6	249	37	1607	—	—	1.1	2.9	—	—	H
7	193	65	801	—	—	1.3	2.8	—	—	H
8	305	119	447	—	—	1.4	4.9	—	—	H
9	496	125	481	—	—	1.3	2.5	—	—	H
10	213	680	104	495	—	1.0	1.4	10.3	—	KH
11	136	38	953	—	—	0.9	1.2	—	—	H
12	298	65	855	—	—	1.0	3.7	—	—	H
13	133	56	716	—	—	3.0	4.5	—	—	H
14	163	69	243	96	755	0.8	0.9	2.4	10.8	HKA
15	228	432	5471	—	—	1.5	19.2	—	—	A
16	215	80	1029	—	—	0.7	1.5	—	—	H
17	253	54	1057	—	—	0.6	2.4	—	—	H
18	152	64	796	—	—	1.2	12.1	—	—	H
19	97	36	248	—	—	1.2	1.9	—	—	H

Note: ρ stand for resistivity; h stand for thickness.

Figures 2 and 3 show associated VES positions along the strike (SW-NE) and dip (NW-SE) directions, respectively, for a quantitative 2D subsurface geologic model of the research region, which was created from the results of Table 2 in order to completely comprehend the subsurface geology of the area. The weathered layer on (Figure 2a) has a resistivity range of 37 to 125 m, showing clay soil material down to a depth of approximately 7 m on VES 8. Clay soil materials are incompetent as they cause differential dislodgment on engineering structures (Sheriff, 1991), therefore can cause collapse. Around VES 10, the geologic structure was observed (Figure 2a), making this region of the research area completely unsuitable for a foundation. Bedrock resistivity varies from 447 to 1607 Ωm and occurs as shallow as 3.8 m around VES 9 (Figure 2a). This resistivity range is an indication of a competent layer for foundation placement due to the stress holding capacity of the material as described (Sheriff, 1991; Olorunfemi, et al., 2002) (Table 1). Also, Figure 2b revealed weathered later resistivity values ranging from 36 - 80 Ωm , which indicates clay

material, to the depth of 3 m, except VES 18 where the overburden thickness is up to 17 m. The thick overburden around VES 18 is likely due to bedrock depression, which must be taken into consideration during foundation designs.

Figure 3a revealed an overburden layer (consisting the topsoil and weathered clay soil) of depth of about 5 m with a resistivity values implying loose and incompetent soil, as presented on Table 1. Bedrock resistivity values are between 891 and 1958 Ωm , occurring at a depth between 3 and 5 m (Figure 3a). This layer is considered competent for foundation placement. Figure 3b revealed clay weathered layer of resistivity between 43 and 119 Ωm . However, the cumulative thickness of the overburden layer to the top of the competent soil is between 5 and 7 m (Figure 3b). Thick overburden, up to 13 m, around VES 18 may be as a result of subsurface/basement depression, which must be taken into consideration while designing the foundation type.

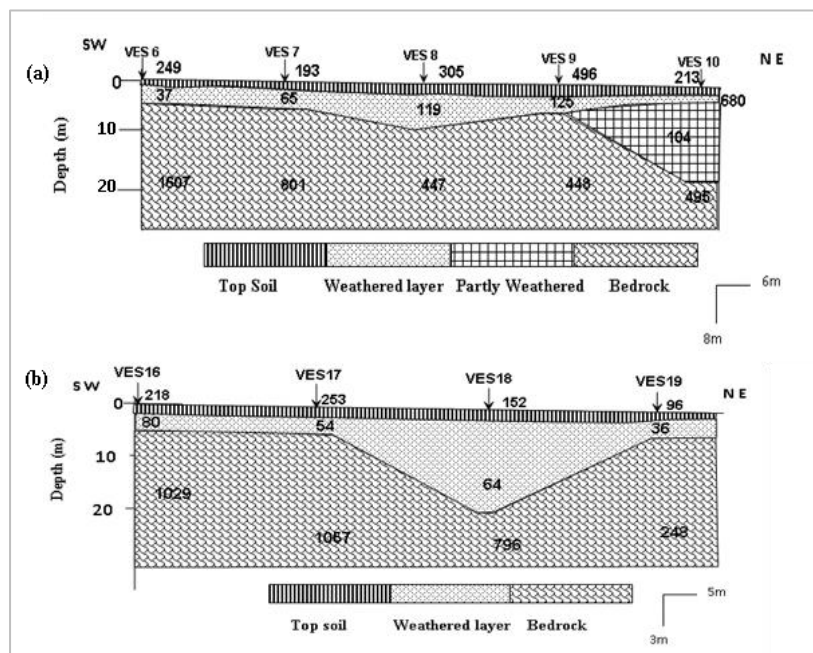


Figure 2: Geoelectric segment along the Strike (SW-NE) direction linking (a) VES 6,7,8,9 and 10; and (b) VES 16, 17, 18 and 19.

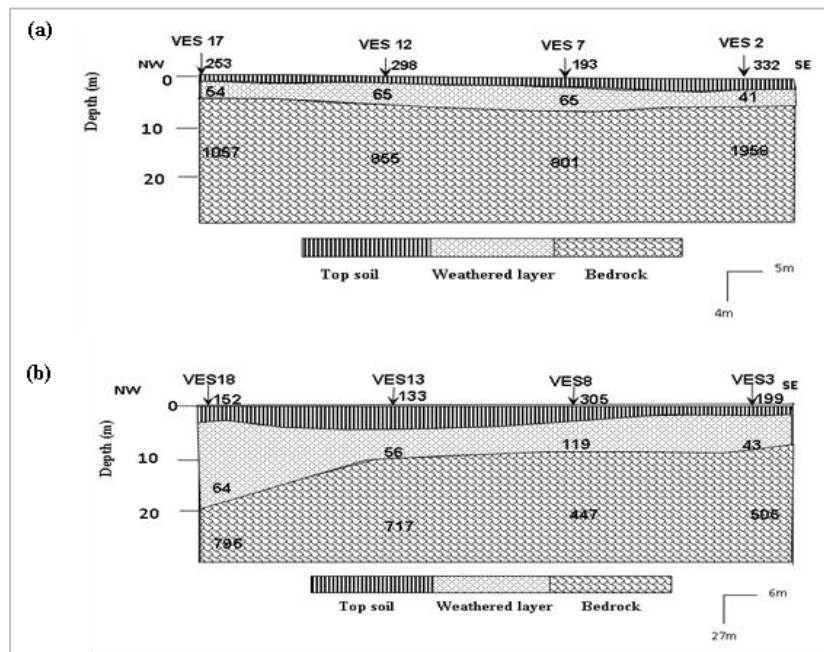


Figure 3: Geoelectric segment along the dip (NW-SE) direction linking. (a) VES 17, 12, 7 and 2; and (b) VES 18, 13, 8 and 3.

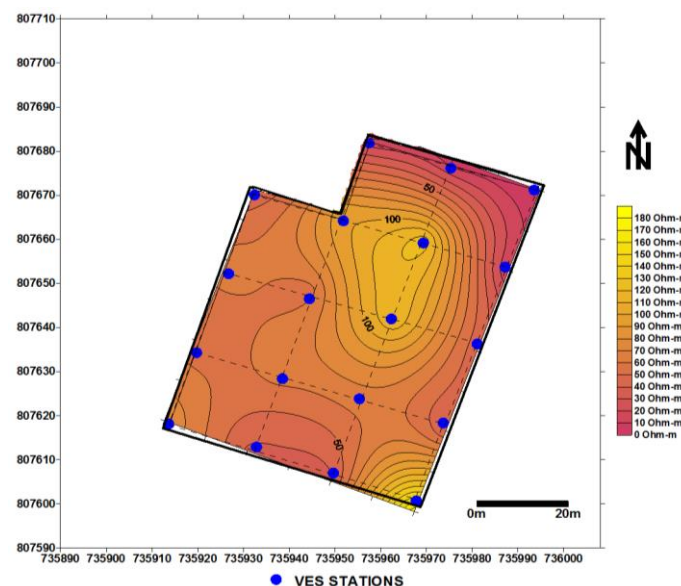


Figure 4: Isoresistivity Map of the Overburden layer

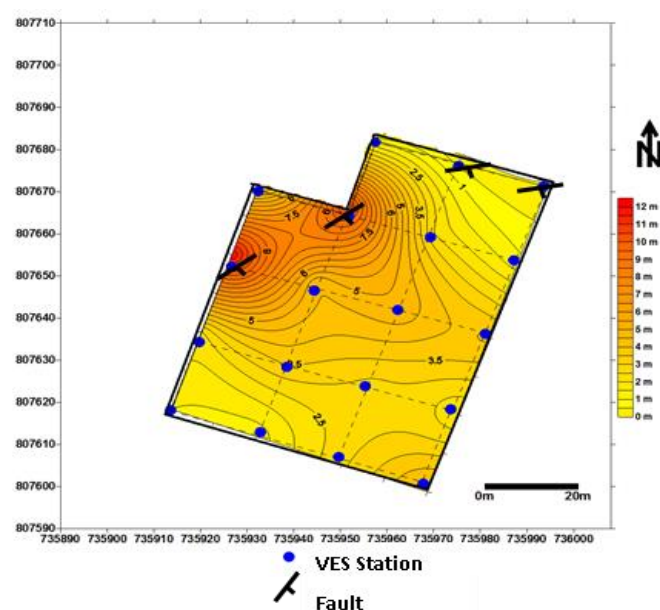


Figure 5: Isopach Map of the Overburden Layer

In order to provide a general impression of the near-surface soil features of the research area, isoresistivity (Figure 4) and isopach (Figure 5) maps describes the spatial distribution of the overburden layer (that is, topsoil and incompetent weathered layer) in terms of resistivity and thickness respectively. Figure 4 demonstrated that the overburden layer is made up of clay and sandy clay formations based on the overall resistivity values. This renders the layer incompetent to build engineering structures. Figure 5 revealed that this incompetent overburden layer is thin towards the south, central and north-eastern

Part of the study area with thickness between 2 and 5 m. Presence of fault are observed towards the western and northern part of the study area (Figure 5; Table 2). The existence of this geologic structure may be the cause of the high thickness of the overburden layer (up to 12 m) at this area (Figure 5).

4.2 Geotechnical Investigation

Summarized GTECH analysis is presented in Table 3. The soil analysis reveals 4.20 to 8.20 % of Natural Moisture Content (NMC) which is considered very low. Considering discrepancies in NMC of soil due to the

amount of rainfall, depth at which samples is collected as well as textural value of the soil; Jegede, 2000 recommended that such soil showing NMC value of 4.20 to 8.20 % underlain the area under study will not pose severe threat to the propose structure provided the strength/intensity of rain is reasonable for the period of rainy seasons.

For Consistency Limit (CL) test (Table 3); moderate Liquid Limit (LL) ranging from 25 to 40 %, moderate Plastic Limit (PL) between 18 and 30 %, and 8 and 22 % Plastic Index (PI) were recorded. Soils having high values of LL and PL are not recommended for foundation material. The intermediate LL and PL values in the study area point toward the clayey character of the soil/formation. However, FMWH, 2010 recommends standard values of 40%, 12% for LL, PI respectively for sub grade materials. The maximum recorded PI of the soil samples is 21.7% at the Northern part of the study area. This result confirms the clayey nature of the soil material as interpreted from geophysical survey (Figure 4). A moderate PI value of about 20% (Table 3) is moderately good for engineering material (Jegede, 2000), and values below it are considered good whereas those with a value higher than that are deemed incompetent.

Table 3: Summarized Geotechnical Analysis Results

Sample	NMC	PSA 0.075mm	CL				SS		CT	
			LL	PL	PI	LS	UCS	UDSS	MDD	OMC
1	4.20	35	30.20	20.90	9.3	8.60	230	115	1940	10.5
2	6.13	42	35.80	20.0	15.80	10.7	130	65	1885	15
3	6.21	30.10	25.90	—	—	6.4	140	70	1775	14.90
4	5.25	39.50	29.20	21.20	8.2	7.1	180	90	1820	12.90
5	8.16	50.10	39.80	18.10	21.7	10.7	120	60	1635	21.90

Note: LS-Linear shrinkage, UCS-Unconfined Compression Strength, UDSS- Undrained Shear Strength, MDD- Maximum Dry Density, OMC- Optimum Moisture Content.

In general, PI of the soils samples 1 and 4 within the area were lower than the 12% maximum suggested by (FMWH, 1997), the soil possess good engineering material as competency of the soil is defined by the lower PI, which is consistent with geophysical results of these areas (soils sample 1 and 4) which showed that the area is dominated by sand and clayey sand. The Linear Shrinkage (LS) value of the tested soils ranges between 6 and 11 % (Table 3). Brink et al (1992) put forward that soils with LS lower than 8% are apparently inert and are fairly good foundation materials. Considering that the average value of the LS is 8.7% within the study area, the soils may swell and fall away during dry and wet seasons, which should not be taken for granted in the course foundation design.

Assessment on the Shear Strength (SS) revealed Unconfined Compression (UC) strength ranges between 120 and 230 KN/m² (Table 3) whereas the Undrained Shear Strength (UDSS) ranges from 60 - 115 KN/m². The elevated values of UC strength signify a substantial percentage of clay within the samples. Comparing the SS result with the 103KN/m² minimum acceptable standard of FMWH, 1997, the subsoil within the study area possesses reasonably high strength property. The intention of the test is to get hold of compressive strength for the soils that have sufficient cohesion to allow testing in the unconfined state. Soil samples such as soft clays, dry and crumbly soils, silts and/or sandy samples generally display higher UDSS (ASTM, 1996).

Grain size distribution and grading curves for all the samples (Table 3) revealed moderately elevated percentage of finer soil particles, at Percentage Passing 0.075 mm, ranging from 35 to 50%. The soils samples from the study area to a large extent graded well. Generally, the tested soils have a Percentage Passing 0.075 mm with an average of 41%. FMWH (2010) advocated 35% maximum rating of foundation formation (Table 3). These ranges of values reveal that the overburden layer is majorly characterized by clay and clayey sand materials, such materials will be liable to swelling in the event of a rise in water table. This result agrees with the initial geophysical results of overburden layer composition mainly of clay material.

Towards ascertaining desirable load-bearing properties (density) of the soil within the study area, compaction test from Maximum Dry Density (MDD) reveals density between 1635 and 1940 Kg/m³; and Optimum Moisture Content (OMC) between 11 and 21.9 % (Table 3). At a MDD of 1940 Kg/m³, OMC is as low as 12.5%. These values demonstrate that the soils react steadily to compaction, Jegede, 1999; suggested high MDD and low OMC soil material for a foundation purpose.

5. CONCLUSION

An integrated GPHY and GTECH study were performed with the intention of understanding the subsurface soil properties prior to construction of an engineering structure. In achieving the research purpose, nineteen (19) VES stations, for GPHY sounding; and five (5) locations, for GTECH soil sample analysis, were occupied. The GPHY results revealed that the topsoil and weathered layer is characterized with clay material, with average thickness of about 5 m, which was referred to as overburden layer to the competent sandy layer suitable for engineering foundation. 2-D Geo-electric sections from GPHY sounding also unearthed the undulating nature of the subsurface topography with depth to competent layer between 5 and 12 m. GTECH analysis show that the soils within the study area is generally characterized by low NMC between 4.20 to 8.20 % and Percentage Passing of 0.075 mm sieve greater than 35% in most areas (an indication of the clay nature of the soil). Consistency Limits of the soils revealed LL of 40% maximum and average PI of 20%. Although, at these Consistency Limits values, the soil is expected to experience moderate swelling, however, the values are within the average values suggested by (FMWH, 2010) for sub-grade materials. The general Linear Shrinkage of the soils has an average of 8 %, which implies expansiveness of the soil. Overall GPHY and GTECH results show that the weathered layer is clayey in nature and is not good foundation material. The clay material will need to be excavated and the undulating nature of the depth to competent sandy layer should be considered while designing the foundation type. This research revealed the importance of GPHY and GTECH methods of investigation, as both methods complemented each other limitations well. GTECH analysis provided insitu and quantitative subsurface soil properties while GPHY analysis provided spatial distribution of subsurface parameters as well as the delineation of geologic structure, which could serve as threat to the engineering structure. This research will not only ensure a proper design and planning of the proposed structure but will also showcase the significant of GPHY and GTECH investigation as a yardstick to minimize structural failure.

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REFERENCES

- Adesida A, Omosuyi GO. 2005. Geoelectric investigation of bedrock structures in the mini campus of the Federal University of Technology, Akure, Southwestern Nigeria, and the geotechnical significance. *Nig. Jour. Pure Appl. Phys* Vol. 4, pp. 32-40
- Adeoti L, Ojo AO, Adegbola RB, Fasakin OO 2016. Geoelectric assessment as an aid to geotechnical investigation at a proposed residential development site in Ilubirin, Lagos, Southwestern Nigeria. *Arab J Geosci* 9, pp. 338.
- Aghamelu OP, Odoh BI, Egboka BCE 2011. A geotechnical investigation of the structural failures of building projects in parts of Awka, southeastern Nigeria. *Indian J Sci Technol* 3, pp. 1119-1124
- Akinlabi IA, Adeyemi GO 2014. Determination of empirical relations between geoelectrical data and geotechnical parameters in foundation studies for a proposed earth dam. *Pac J Sci Technol* 15, pp. 278-287
- Akintorinwa, OJ and Adesoji, JI 2009. Application of Geophysical and geotechnical investigations in Engineering site Evaluation. *International Journal of physical sciences*, Vol. 4 (8), pp. 443-454.
- Akintorinwa, OJ and Adeusi, FA 2009. Integration of Geophysical and Geotechnical Investigations for a proposed lecture Room complex at the Federal University of Technology, Akure, SW, Nigeria. *Ozean journal of Applied Sciences* 2(3), pp. 241-254.
- Akintorinwa OJ, Oluwole ST 2018. Empirical relationship between electrical resistivity and geotechnical parameters: A case study of Federal University of Technology campus, Akure SW, Nigeria. *NRIAG J Astronomy Geophys* 7, pp. 123-133.
- Arora KR. 2008. Soil mechanics and foundation engineering (Geotechnical Engineering). Standard Publishers Distributors, Delhi.
- Bharti, AK., Pal, SK., Priyam, P, Kumar, S, Shalivahan and Yadav, PK. 2016. Subsurface cavity detection over Patherdih colliery, Jharia Coalfield, India using electrical resistivity tomography. *Environmental Earth Sciences*, 75(5) 443, pp. 1-17. DOI: 10.1007/s12665-015-5025-z.
- Bharti, AK., Pal, SK., Saurab h, Singh, KKK., Singh, PK., Prakash, A., Tiwary, RK. 2019. Groundwater prospecting by inversion of cumulative data of Wenner-Schlumberger and Dipole-Dipole arrays: A case study at Turamdih, Jharkhand, India. *Journal of Earth System Science*, 128(4), pp. 107.
- Bremmer CN. 1999. Developments in geomechanical research for infrastructural projects, in 12th European Conference on soil mechanic and geotechnical engineering: Geotechniek, Special Issue, pp. 52-55.
- Brink ABD, Parridge JC, Williams AAB. 1992. Soil survey for engineering, Clarendon, Oxford.
- British Standard (BS) 1377. 1990. Methods of testing soils for civil engineering purposes. British Standards Institution, London
- Cardarelli E, Donno GD, Ilaria Olivetti I, Scatigno C. 2018. Three-dimensional reconstruction of a masonry building through electrical and seismic tomography validated by biological analyses. *Near Surface Geophysics* 16, pp. 53-65.
- Das P, Pal SK., Mohanty PR, Priyam P, Bharti A.K., and Kumar R. 2017. Abandoned mine galleries detection using Electrical resistivity tomography method over Jharia coal field, India. *Journal of the Geological Society of India*, V90(2), pp. 169-174.
- Fajana AO, Olaseeni OG, Bamidele OE, Olabode OP. 2016. Geophysical and geotechnical investigation for post foundation studies, Faculty of Social Sciences and Humanities, Federal University Oye Ekiti. *FUOYE J Eng Tech* 1, pp. 2579-0617
- Federal Ministry of Works and Housing (FMWH). 1997. General specification for roads and bridges, vol II. Federal Highway Department Lagos, Abuja, pp. 317
- Federal Ministry of Works and Housing (FMWH). 2010. General specification of roads and bridges 2, pp. 137-275
- Gupta RK, Agrawal M. Pal SK, Kumar R, Srivastava S. 2019. Site characterization through combined analysis of seismic and electrical resistivity data at a site of Dhanbad, Jharkhand, India. *Environmental Earth Sciences* 78 (6), pp. 226. <https://doi.org/10.1007/s12665-019-8231-2>.
- Gupta RK, Agrawal M, Pal, SK, Das MK. 2021. Seismic site characterization and site response study of Nirsra (India). *Nat Hazards*. <https://doi.org/10.1007/s11069-021-04767-w>
- Jegede, G. 1999. Engineering Geological Significance of the superficial Deposits in carington Hill Area, country conc, Ireland. *Nig. Journal of sciences* Vol. 28, pp. 153-158.
- Jegede G. 2000. Effect of soil properties on pavement failure along F209 highway at Ado-Ekiti, south-western part of Nigeria. *Journal of construction and building materials*, Vol 14, pp. 311-315
- Khatrri R, Shrivastava VK, Chandak R. 2011. Correlation between vertical electric sounding and conventional methods of geotechnical site investigation. *Int J Adv Eng Sci Tech* 4, pp. 42-53.
- Nwankwoala HO, Warmate T. 2014. Geotechnical assessment of foundation conditions of a site in Ubima, Ikwerre Local Government Area, Rivers State, Nigeria. *Int J Eng Res Dev*. 9, pp. 50-63.
- Oghenero AE, Akpokodje EG, Tse AC 2014. Geotechnical properties of subsurface soils in Warri, Western Niger Delta, Nigeria. *J Earth Sci Geotech Eng* 4, pp. 89-102.
- Ofomola, MO Adiat, .AN, Olagunju, GM and Ako, BD 2009. Integrated Geophysical methods for post foundational studies, Obanla staff Quarters of the federal university of technology, Akure, Nigeria. *Pacific Journal of science and Technology*. 10(2), pp. 93-111.
- Olaleye OK, Enikanselu PA, Ayuk MA 2020. Use of spectral decomposition technique for mapping geologic features of 'Reigh' field, Onshore Niger Delta. *Nigeria Journal of Pure and Applied Physics* 10(1), pp. 1 - 7. DOI: 10.4314/njpap.v10i1.1
- Olayanju GM, Mogaji KA, Lim HS, Ojo TS 2017. Foundation integrity assessment using integrated geophysical and geotechnical techniques: Case study in crystalline basement complex, southwestern Nigeria. *J Geophys Eng* 14, pp. 675- 690
- Olorode DO, Olatinsu OB, Ugwoke EE. 2012. Site investigation using the combination of electrical resistivity technique and CPT: A case study of a coastal area of Lagos, Nigeria, *European Journal of Scientific Research*, Vol. 81(3), pp. 344 - 356.
- Olorunfemi, MO, Ojo, JS and Ojelabi, EA. 2002. Geophysical site investigation of the premises of Idu Flow station. Nigeria Agip company (NAOC) Limited (for multipurpose oil services company limited, Port Harcourt). Technical report.
- Olorunfemi MO, Idornige AI, Coker AT and Bbadiya GE. 2004. On the application of electrical resistivity method in foundation failure investigation – a case study. *Global journal Geol. Sciences*, 2(1), pp. 139- 151
- Omoyoloye, NA, Oladapo, MI and Adeoye, OO. 2008. Engineering Geophysical study of Adagbakuja Newtown Development, South Western Nigerian. *Medwell online journal of Earth Science*, Vol. 2(2), pp. 55-63.
- Oyedele KF. 2009. Engineering geophysical approach to progressive or sudden collapse of engineering structures in Lagos, Nigeria. *The Journal of American Science*, 5(5), pp. 91-100
- Oyedele KF, Okoh C. 2011a. Subsoil investigation using integrated methods at Lagos, Nigeria. *J Geol Min Res* 3, pp. 169-179.
- Oyedele KF, Oladele S, Adedoyin O. 2011b. Application of geophysical and geotechnical methods to site characterization for construction purpose in Ikoyi, Lagos. *Nigeria J Earth Sci Geotech Eng* 1, pp. 87-100.
- Oyediran IA, Falae PO. 2018. Integrated Geophysical and Geotechnical Methods for Pre-Foundation Investigations. *J Geol Geophys* 7, pp. 453. doi: 10.4172/2381-8719.1000453
- Oyedele KF, Olorode DO. 2011. Site investigations of subsurface conditions

- using electrical resistivity method and cone penetration test at Medina Estate, Gbagada, Lagos, Nigeria. *World App Sci J* 11, pp. 1097-1104.
- Pazzi V, Di Filippo M, Di Nezza M, Carlà T, Bardi F. 2018. Integrated geophysical survey in a sinkhole-prone area: microgravity, electrical resistivity tomographies, and seismic noise measurements to delimit its extension. *Eng Geol* 243, pp. 282-293
- Rahnan MA. 1989. Review of the basement geology of south-western part of Nigeria in Kogbe, CA, (ed) *Geology of Nigeria*, Rock view (Nig) limited, jos, Nigeria. pp. 39-59
- Reynolds JM. 2011. *An introduction to applied and environmental geophysics*, 2nd Edn. Wiley, pp. 710.
- Rungroj A, Mark EE. 2015. Application of 2D electrical resistivity tomography to engineering projects: Three case studies. *Songklanakarin J Sci Technol* 37, pp. 675-681.
- Sheriff RE. 1991. *Encyclopedic dictionary of exploration geophysics* (3rd ed.). Geophysical reference series 1, society of exploration Geophysics (SEG) Tulsa, Oklahoma USA.
- Singh KKK, Bharti, AK, Pal, S K., Prakash A., Saurabh, Kumar R., Singh, P.K.. 2019. Delineation of fracture zone for groundwater using combined inversion technique. *Environmental Earth Sciences*, 78, pp. 110. <https://doi.org/10.1007/s12665-019-8072-z>
- Soupois PM, Georgakopoulos P, Papadopoulos N, Saltos V, Andreadakis A. 2007. Use of engineering geophysics to investigate a site for a building foundation. *J Geophys Eng* 4, pp. 94-103.
- Srivastava S, Pal SK, and Kumar Rajwardhan, 2020. A time-lapse study using Self-Potential and Electrical Resistivity Tomography methods for mapping of old mine working across railway-tracks in a part of Raniganj Coalfield, India. *Environmental Earth Sciences*, 79, pp. 332. <https://doi.org/10.1007/s12665-020-09067-3>
- Youdeowei PO, Nwankwoala HO. 2013. Suitability of soils as bearing media at a freshwater swamp terrain in the Niger Delta. *J Geol Min Res* 5, pp. 58-64.

