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Geophysical And Geotechnical Pre-Foundation Site Investigation For Engineering Construction Purpose

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Abstract
Geophysical and geotechnical pre-foundation investigation was carried out as a means for engineering subsurface characterization at a major proposed construction location. The geophysical investigation utilized 2-D subsurface profiling and Vertical Electrical Soundings, combined with geotechnical laboratory analyses carried out in a standard engineering geology laboratory. The 2-D subsurface images delineated three lithologic units; classified as topsoil, weathered layer and fresh basement; with respective resistivity values that ranged between 14 and 39 ohm-m, 21 and 122 ohm-m and 62 and 1965 ohm-m; and depth interval of 0.1-3 m, 2-12 m and < 10 m to basement. Characteristic A- and H- type curves of 3-layer model with the H- model curve starting with decreasing resistivity, diagnostic of incompetent subsurface layer constitutes 80% occurrence of the investigated stations. The resistivity and thickness parameters of layers identified from the geo-electric sections are 6-38 ohm-m / 0.6-3.5 m (topsoil (clayey)); 4-89 ohm-m / 2.1-10.9 m (weathered layer); 162-456 ohm-m (fresh basement). Subsurface resistivity structure images and sections mapped basement depressions in western, eastern and southern flanks along the investigated traverses. The geotechnical results show high consistency limits with liquid limit, plastic limit, shrinkage limit and plasticity index ranging from 34-41%, 19-21%, 9-11% and 15-21% respectively. There exist significant correlation and inter-relationship in the geophysical and geotechnical results with indication that the topsoil and weathered layer are mostly of less compacted and compressible soil properties. The proposed site is generally underlain by weak and incompetent near-surface foundation substratum. The study demonstrated the effectiveness of engineering geophysics investigation approach as an indispensable and veritable tool in complimenting the traditional geotechnical test routine in engineering site characterization procedures.

Keywords: *Subsurface, Characterization, Foundation, Resistivity, Atterberg limits, Depression*

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I. Introduction

Globally, the news on building collapse is no longer a new phenomenon but has become a recurring decimal with records of incessant cases reported in the last few decades. In developing countries with focus on Nigeria, building collapse has been identified as largely human induced occurrences (Akujobi, 2013), now recurring with no respite in sight. Building collapse is catastrophic in nature, usually claiming lives, causing severe injuries and loss of investments. Statistical records show that up to 379 cases were recorded, several unrecorded, scores of injuries and properties worth billions of naira have been lost to building failures and collapse across Nigeria in a space of 25 years (Windapo, 2006). Another report analysis established that 541 building collapse incidents were witnessed in all states of Nigeria and the Federal Capital Territory between 1974 and 2022. Possible and effective measure of control or prevention of the incessant failure of buildings within our society in recent times has generated concerns, prompting the entire citizenries to continue to ponder on its causes and solutions. Apart from engineering design errors, the incessant occurrence of building collapses could be attributed to inadequate knowledge of the nature of the subsurface materials which is key to the stability of building foundation. Foundation erected on incompetent or less competent earth layers poses serious threat to the building which can also lead to collapse (Amadi *et al.,* 2012; Adelusi *et al.,* 2013; Faleye *et al.,* 2022).

The absence of site investigation with the view of cutting overall cost of engineering projects is a non-professional practice that should be avoided or legislated against at all levels. A holistic site investigation, incorporating non-destructive methods having advantage of reasonable depth delineation will greatly help in determining the nature and properties of the subsurface conditions. For engineering structures to have long life span and provide safety for lives and properties, regardless of the geological environment; adequate pre-construction investigation must be carried out to delineate and assess the strength and competence of the subsurface host materials. For instance, weak foundation could be precipitated by subsoil foundation materials (essentially underlying geologic layers).

Egunjobi and Adebayo (2016) highlighted environmental factor such as geographical location for consideration with respect to building collapse. Albeit, this primarily scales down to geological conditions of the substrata underlying building foundations. Again, public opinions have advocated the designing of the building's foundation to match the load it would carry; however, where this is done, there still exist possibilities of failure, if the geological conditions (especially at depth) do not have the carrying capacity for such load. Undoubtedly, it is important to state that spatial soil layers expected to bear and transmit building loads (live and dead) must be adequately investigated at the pre-construction stage, since little or no remedial effort could attend to foundation failures.

Amongst recommendations made in the past, emphases have often been laid on carrying out soil test. It is however important to note that soil test goes beyond sampling and laboratory analysis. More so, it entails delineation and investigating the geological condition or in-situ tectonic structural features that could pose risk to building foundation. Poor soil test is undertaken when appropriate professionals are not engaged, thereby discountenancing the hidden and deep-seated geological information that are required to aid proper design plans. The current practice in the building industry has shown that geoscientists are often sidelined in execution process of building projects (major infrastructures inclusive); even though the bill of quantity usually reflect cost for their services. Therefore, the building industry should discourage professionals who extend their services beyond the scope of their competence (Egunjobi and Adebayo, 2016); and be deliberate to acknowledge the proficiency of geoscientists in building project cycle. Thus, government and concerned professional associations should live up to expectation in correcting this abnormal norm. Government, in synergy with regulatory councils and the public have huge responsibility to put in place a working system that would frustrate the inhumane actions of greedy professionals and developers in the building industry.

Previous works in geosciences have attributed these failures to lateral inhomogeneity of the subsurface, non-permissible differential settlement and presence of shear or weak zones (such as fault, fracture, and joint) beneath the foundation buildings (Drobiec *et al.*, 2021). In areas of thick overburden cover, the materials could have variety of engineering properties. Some foundation beds may be very weak especially where the clay content is significantly high (Soupios *et al.,* 2007, Faleye *et al.,* 2022). The quantum of settlement occurring below a structure is chiefly governed by the type of rocks and soils existing below it (Garg, 2007); thus emphasizing the importance of geology in building construction practice. Subsurface characterization using standard drilling methods which offers point measurements do not provide information to accurately evaluate the true distribution of geologic parameters beneath ground surface at many sites (Holt *et a*l., 1998). Hence as complement to drill hole tests and geotechnics; geophysical technique can provide broad composite images of the subsurface over large areas at relatively lower cost and higher speed and as well increase the confidence level on foundation stability against building collapse.

Geoscientists have engaged in significant foundation studies involving subsurface geo-electric characterization, few of these authors engaged some traditional civil engineering soil test methods in addressing the challenge of building collapse incidences (Olorunfemi and Meshida, 1987; Ayolabi *et al*., 2004; Sudha *et al.,* 2009; Akintorinwa and Abiola, 2011; Faleye and Omosuyi, 2011; Adelusi *et al., 2*013; Ayuni *et al.,* 2018; Onsanchi *et al.,* 2018; Aigbedion *et al*., 2019; Faleye *et al.* 2022). In this study, pre-foundation site characterization using geophysical method involving 2-D imaging and Vertical Electrical Sounding (VES) techniques; and geotechnical laboratory analyses were integrated as complimentary investigation tools at a proposed major engineering construction project location. The study aims to provide information on the indispensable relevance of engineering geophysics as an effective approach and complementary tool in engineering site investigation.

II. Description of Study Environment

The study area is located outskirt of Akure metropolis, off Akure-Ilesha Express Road, Ondo State. It is situated between the UTM coordinates of Eastings 736283 - 736638 mE and Northings 808239 - 8088422 mN (Figure 1). The area is relatively flat with elevation ranging between 368 – 382 m and properly connected by a major tarred road and some footpaths that are easily accessible. The climatic condition is that of the sub-equatorial belt of the tropical rain-forest with evergreen and broad-leaved trees. The area is underlain by the Precambrian Basement Complex rocks of Southwestern Nigeria. The rocks include migmatite gneiss, quartzite, biotite granite, charnocknite and porphyritic granites (Figure 2). The study area exhibits varieties of structures such as foliation, schistocity, folds, faults, joints and fractures. Hydro-geologically, groundwater in the area of study is contained in weathered and fractured basement aquifers (Olorunfemi and Fasuyi, 1993). The former is derived from chemical alteration processes while the latter is the product of tectonic activities. The weathered layer aquifer may occur singly or in combination with the fractured aquifer (Bayode *et al*., 2006).

III. Material and Methods

Geophysical investigation

The primary concern in any engineering site investigation is the mapping of steeply dipping linear structures such as faults, cavity, metallic drums, basement depression, buried stream channels, water bearing horizons and depth to the bedrock. Thus, the geophysical aspect of the investigation employed the electrical resistivity method. The dipole-dipole electrode array was adopted for the combined horizontal profiling and vertical electrical sounding; while Schlumberger electrode array was engaged for the depth sounding. For the dipole-dipole data acquisition, five (5) traverses were established across the study site in the east-west and north-south directions with length range of 40 - 50 m (Figure 1). To ensure possibility of delineation of minor and major near surface anomalies; inter-electrode separation (a) was taken to be 5 m and inter-dipole separation factor (n) ranged from 1 to 5. Identification of anomalous structures was made possible by generating inverted 2-D subsurface images of the field data. The inversion program uses an implementation of the smoothness constrained least-squared method based on the Gauss-Newton optimization technique. The good quality of acquired data is expected to result in close similarity to the theoretical data and significantly low RMS error for the inverted 2-D resistivity structures. The choice of fifteen (15) depth sounding locations, involving the Schlumberger electrode array was constrained by identified features on the 2-D subsurface images. The analytic method of interpretation was applied using partial curve matching technique. The method utilizes two layer model curves with their corresponding auxiliary curves. The curves were matched and the layers' resistivities and thicknesses were determined. These were then used as starting models within a computer program environment with mathematical algorithms for curve-fitting iteration process. The program basically determines a resistivity model that approximates the measured data within the limits of data errors which is in agreement with all prior information. Human errors often associated with manual interpretation are thus reduced to minimum. Geo-electric sections along the traverses were generated using derived geo-electrical parameters from the above process. A high accuracy Ohmega resistivity meter was used for the geo-electrical data acquisition.

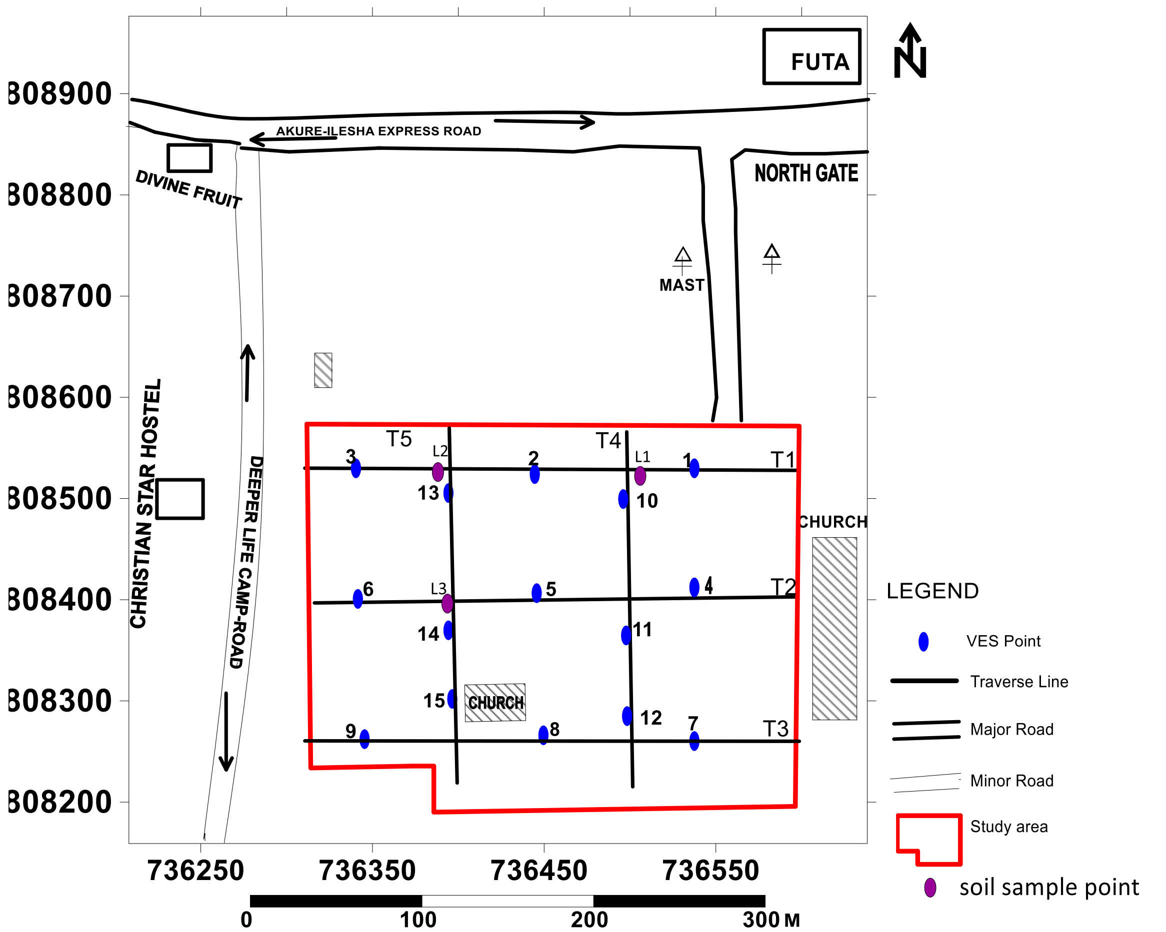


Figure 1: Data acquisition map for the study area

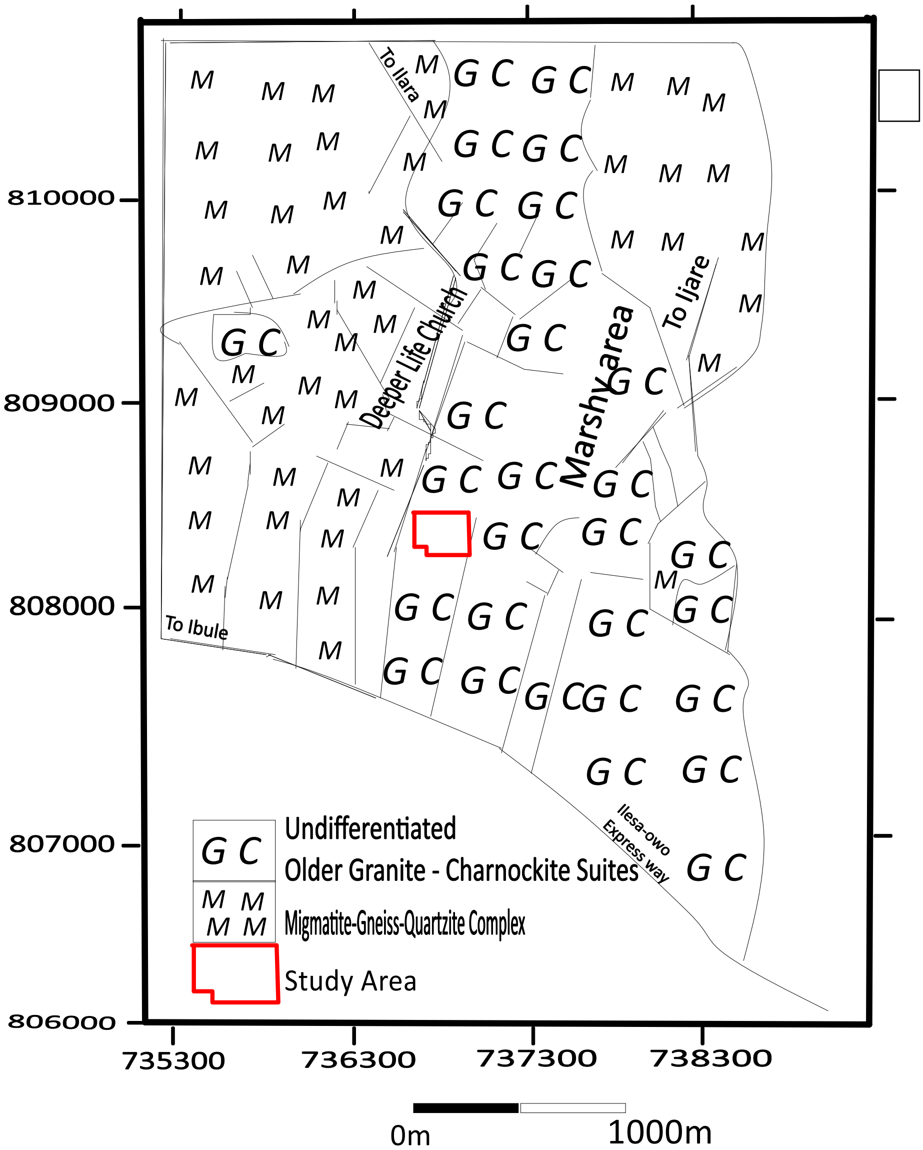


Figure 2: Geological map of the Study Area (modified after Alagbe and Faleye, 2020)

Geotechnical investigation

Geotechnical engineering is the branch of geology/civil engineering concerned with the engineering behavior of earth materials. The objectives of soil investigation are to investigate soil geological condition; provide recommendations and design criteria for construction. It consists essentially of drilling and sampling. Samples collected at the study site were analyzed for geotechnical parameters. The geotechnical analyses involve Atterberg tests. These tests were carried out in a standard engineering geology laboratory, in order to determine the plastic limit, liquid limit, plasticity index and grain size distribution of the soil samples. The plastic and liquid limit, otherwise known as consistency limit were carried out to observe the plasticity of soil samples using the plasticity chart. The Atterberg limits are basic measure of the nature of fine-grained soil. Depending on the water content of the soil, it may appear in four states, solid, semi-solid, plastic and liquid. In each state the consistency and behaviour of a soil is different; thus its engineering properties. The boundary between each state was defined based on a change in soil behaviour. The Atterberg limits were used to distinguish silt and clay. Apparatus used are oven, moisture can / frying pan, mixing knives, spoon, weighing balance and silica gel desiccators.

IV. Results and Discussion

Geo-electric subsurface characterization

2-D resistivity subsurface images

Beneath Traverse 1, delineated geo-electric layers were interpreted as clay, weathered basement and fresh basement (Figure 3a). The top layer is characterized with very low resistivity values which range from 17 - 32 ohm-m; with depth range of 0.1 – 2.5 m. The low resistivity range may been precipitated by the water logged clayey material within the topsoil zone. Underlying the topsoil is the weathered layer (clayey) of relatively low resistivity value ranging from 21 – 46 ohm-m and depth range of 2.0 – 9.5 m. These zones are made up of low foundation integrity attributes. Underlying the weathered layer is the fresh basement whose resistivity value range from 63 -124 ohm-m. The resistivity value of the fresh basement appears to have been subsumed by the overlying saturated and clayey weathered layer; hence the relatively low resistivity range. The depth to top of the fresh basement range between 4 and 9 m. Traverse 2 presents top soil resistivity values varying from 14 - 35 ohm-m and thickness up to 3 m (Figure 4a). The weathered layer is characterized with relatively low resistivity values ranging between 43 and 66 ohm-m and with thickness of 3 - 5 m. The fresh basement is of relatively low to high resistivity values ranging from 100 - 792 ohm-m and depth to top is approximately 5 m. Region of extremely low resistivity, observed between stations 6 and 9 may have been precipitated by the completely water logged condition of near-surface materials at the study site.

The 2-D resistivity subsurface image along Traverse 3 (Figure 5a) features low resistivity topsoil (28-39 ohm-m) with depth extending up to 3 m. The low resistivity observed is indicative of clayey material or observed fluid streaming at the surface level. The top soil is underlain by relatively low resistivity (36 – 122 ohm-m) weathered layer and layer depth (3 – 6 m). The low resistivity observed within the layers is indicative of generally incompetent materials classified as clay. Beneath the weathered layer is a resistive basement with resistivity ranging from 152 – 1965 ohm-m. Depth to basement top is minimum at 3 m. Basement structural depression is suspected to exist beneath the traverse. Similarly, Traverse 4 exhibited top layer of relatively low resistivity range (23 - 29 ohm-m) and thickness range (0.1 – 3m) (Figure 6a). The delineated weathered layer resistivity and depth range from 38 - 110 ohm-m and 2.5 – 8 m. The resistive fresh basement (> 500 ohm-m) was delineated at depth of 4 – 8 m. Resistivity value range of 16 – 27 ohm-m and thickness of about 2.5 m characterize the topsoil beneath Traverse 5 (Figure 7a). The weathered stratum which underlies the top layer has resistivity value of 30 – 44 ohm-m and thickness not greater than 6 m. The fresh basement, whose resistivity value range between 62 and 127 ohm-m was masked by overlying generally low resistivity topsoil and weathered layer; hence appears to have been merged with the overlying layer.

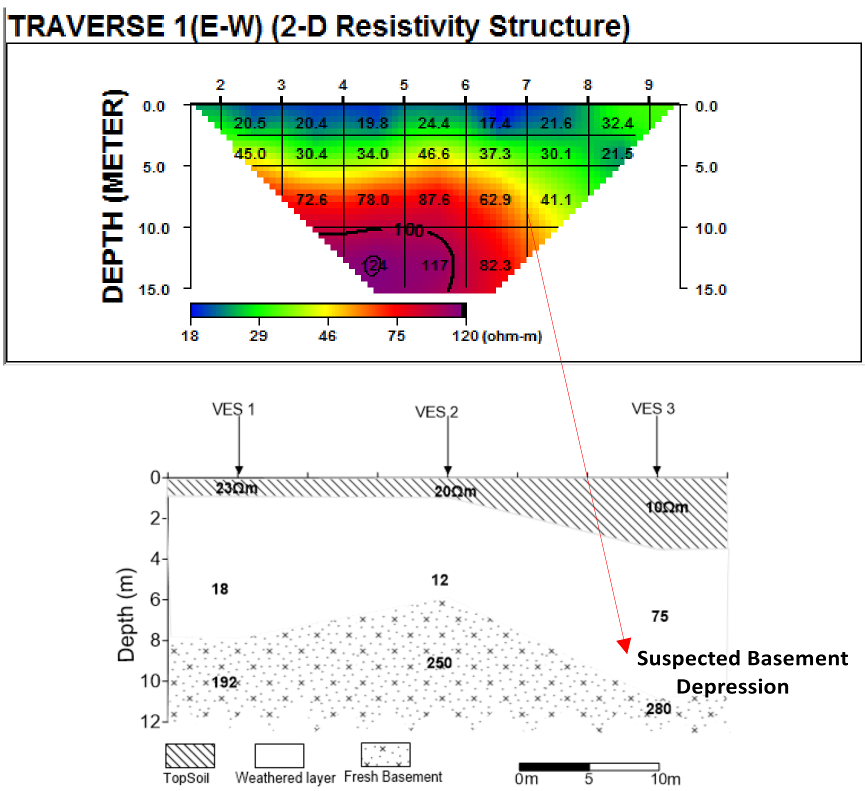


Figure 3: 2-D resistivity structure and geo-electric section for Traverse 1

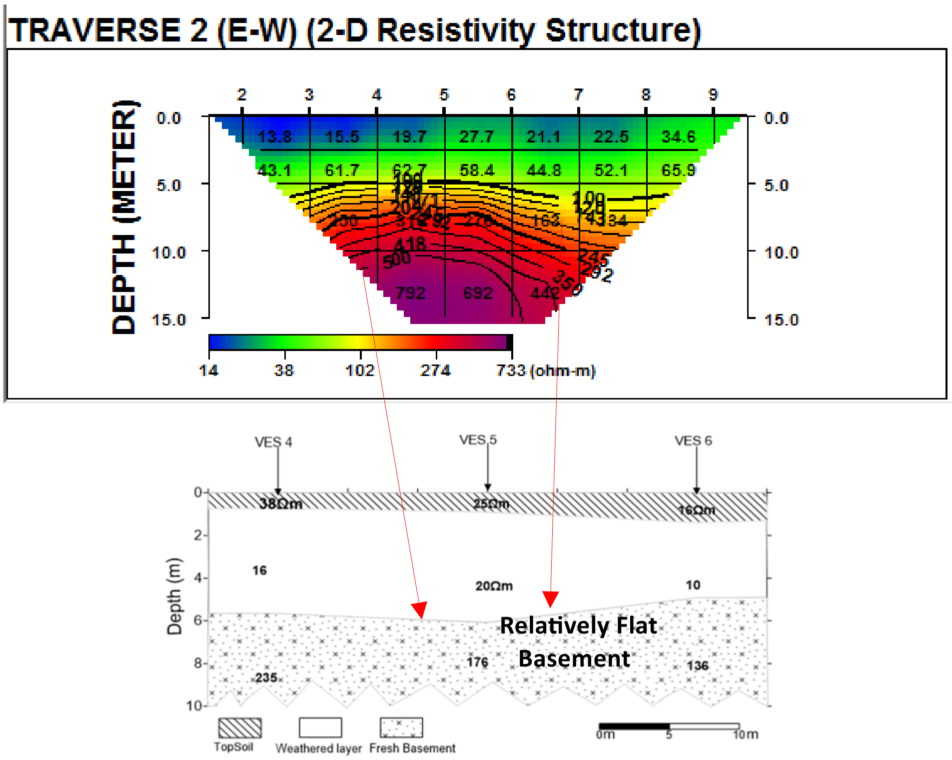


Figure 4: 2-D resistivity structure and geo-electric section for Traverse 2

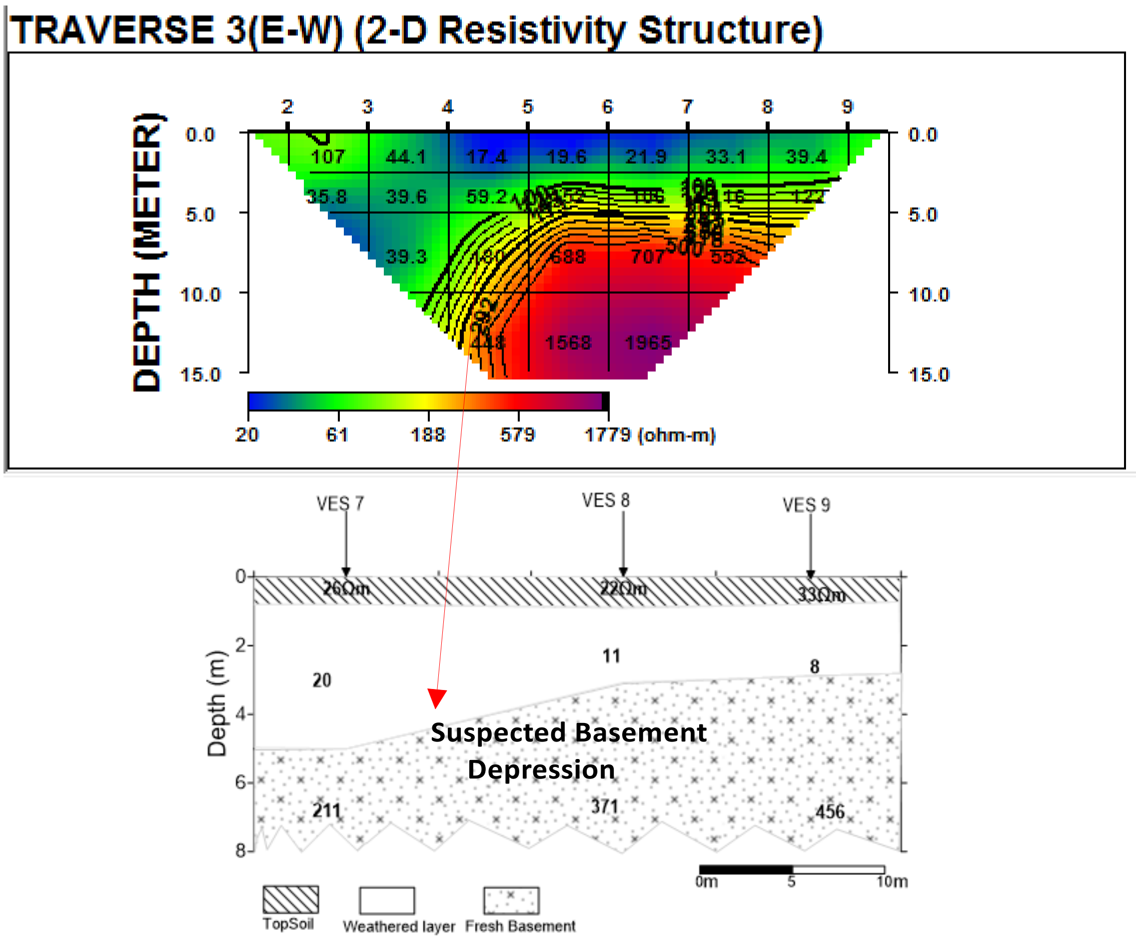


Figure 5: 2-D resistivity structure and geo-electric section for Traverse 3

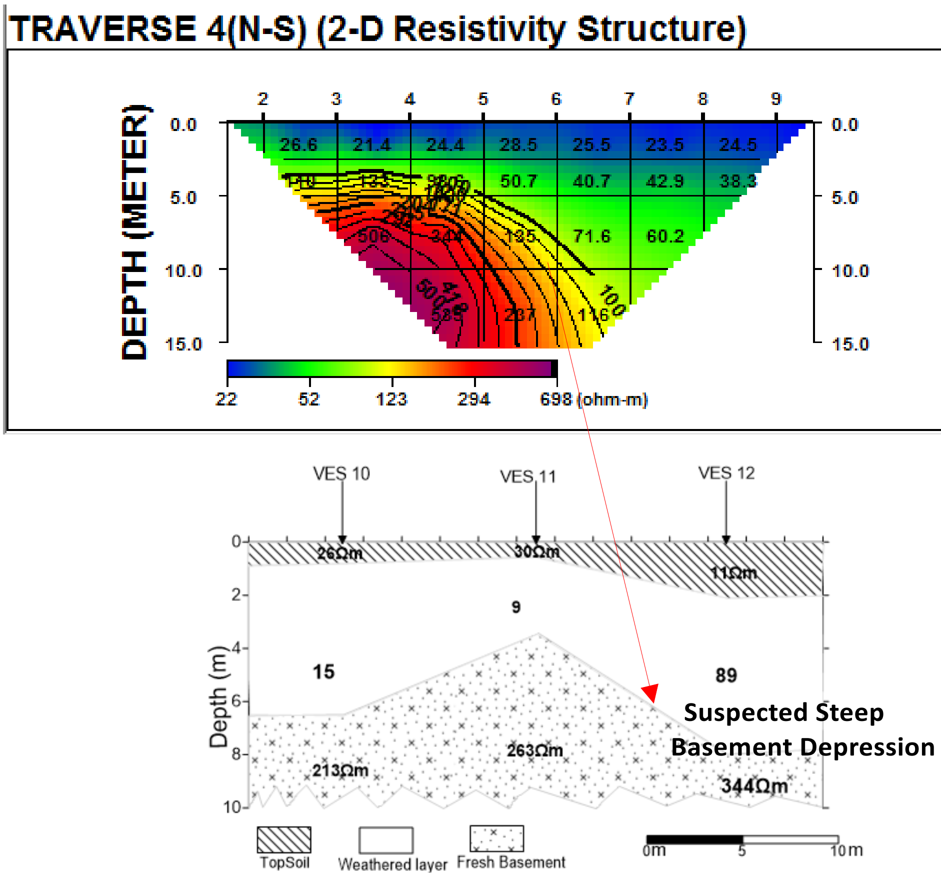


Figure 6: 2-D resistivity structure and geo-electric section for Traverse 4

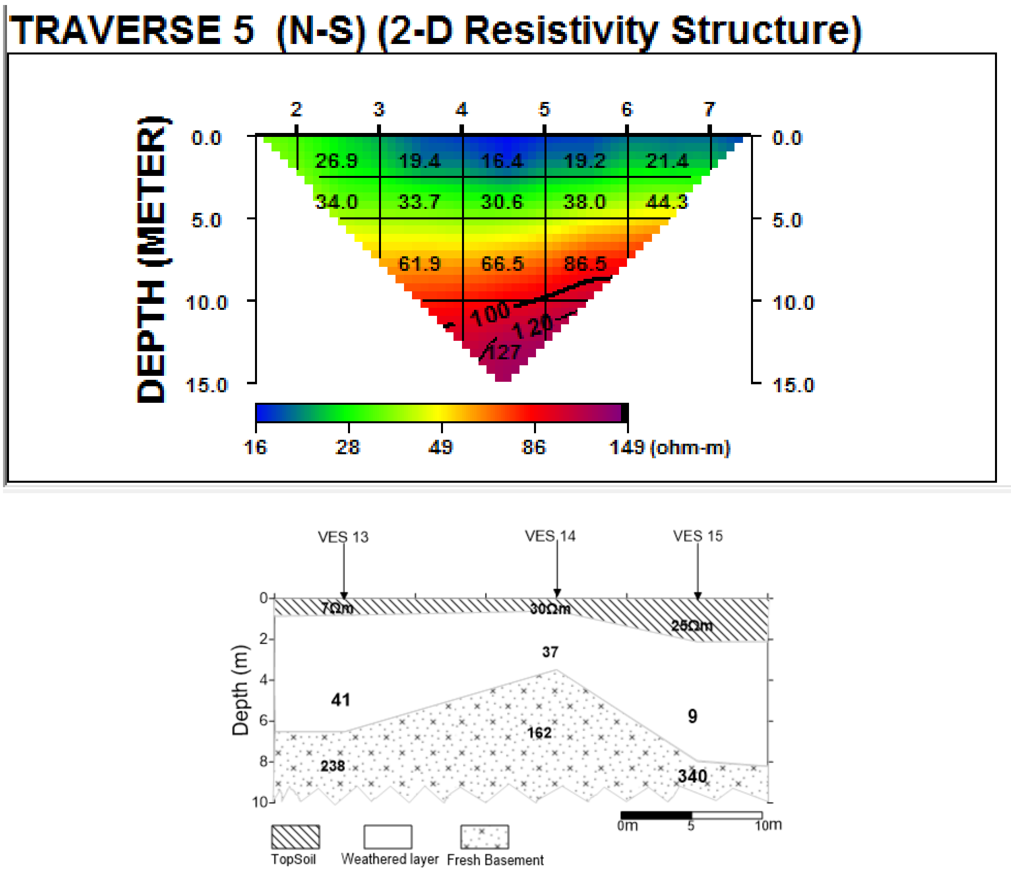


Figure 7: 2-D resistivity structure and geo-electric section for Traverse 5

Vertical electrical soundings profiles / Geo-electric sections

The Vertical Electrical sounding (VES) interpretation result presents two 3-layer major curve types; namely A and H obtained from the study location Figure 8. This suggests two possible subsurface layer situations (Adiat *et al*., 2017). The A curve is characterized with increasing resistivity value with depth which is indicative of a fairly competent material; whereas, the H curve is characterized by relatively low resistivity (less competent) intermediate layer, it constitute 80% occurrence of the investigated stations. The 2-D resistivity structures and the geo-electric sections show that the topsoil is generally characterized by very low resistivity values (generally < 50 ohm-m) and composed of clayey soil within swampy environment. The weathered layer which underlies the topsoil, presumed to be clayey, is inundated by mostly extremely low resistivity with significantly thick column. The fresh basement, though identified as the competent layer has resistivity value suspected to have been submerged by the overburden resistivity effect (Figures 3 - 7).

Geotechnical results

Particle sizes distribution

The particle size distribution charts show the distribution of particles in the soil and are presented as particle size curves and particle size distribution tables. The three samples collected from Location 1, Location 2 and Location 3 fall within clay, sand and gravel sorting. The analysis shows average percentage particle distribution of sand, clay/silt and gravel as 58.1%, 40.5% and 1.4% respectively. Typical grain size result chart and table show that the soil particles contain highest percentage of sand, followed by clay and silt (Figure 9 and Table 1). The result presents a well sorted and graded particle distribution. The Particle size distributions of the tested soil samples are indicative of significantly high percentage clay/silt content (Location 1 = 45.5%, Location 2 = 37.2% and Location 3 = 38.9%). This finding is in agreement with the subsurface geo-electric lithology parameters.

Atterberg limits

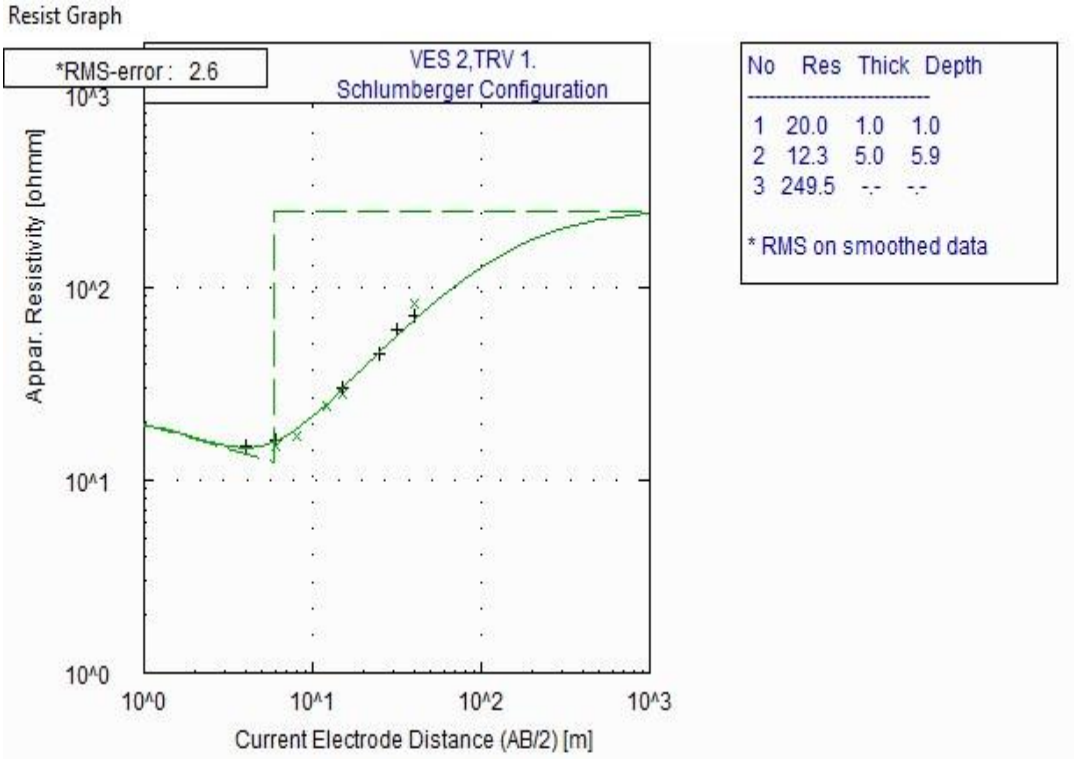
The Atterberg limits consist of plasticity index, liquid limit, plastic limit and shrinkage limit. The plasticity index ranges from 15 - 20%, showing medium to high plasticity and has tendency to pose problem to engineering structures (Burnister, 1947; Holtz and Gibbs, 1956). Liquid limit is the minimum water that a soil will contain before it begins to flow as a liquid. The obtained liquid limits range between 34% and 41%. This threshold is considered not suitable for engineering construction purpose. The plastic limit and shrinkage limit of the soil samples have ranges of 19 - 21 % and 9.1 – 11.0 % respectively. The plastic limit values implied high clay content. Soils with high values of plastic limits are considered poor as foundation materials and not suitable for engineering construction. Shrinkage limit represents the moisture content at which fine-grained soils do not change volume on drying. Thus, the shrinkage limit values for the soil are characterized with high potential swelling capacity adjudged not appropriate for construction purpose. Typical Atterberg limits chart for location 1 is presented in Figure 10.

Geo-electric subsurface correlation and deductions

Mapping of bedrock topography play fundamental role in engineering site characterization; especially where near-surface geologic textural materials are of insignificant load bearing capacity. Since structures' foundations always undergo equilibrium balancing through the process of differential settlement; the nature and geometry of the bedrock topography beneath these structures are therefore of importance in safety and management concerns. The 2-D resistivity images and geo-electric sections derived from the electrical resistivity measurements showed close correlation in bedrock topography mapping in this case study. Relatively flat basement surface was identified beneath Traverse 2 (Figure 4); however, basement depressions were delineated in the western and southern flanks along Traverses 1 and 4 respectively (Figures 3 and 6). Similarly, suspected basement depression in the eastern direction was identified along Traverse 3 (Figure 5). These details are helpful in identifying areas or zones where reinforcement efforts could possibly be necessary.

V. Conclusion

Pre-foundation study involving the integration of Vertical Electrical Sounding (VES), 2-D subsurface imaging and geotechnical investigation was carried out at a proposed site as a means to determine the competence of the subsoil material for proposed major engineering structures. The 2-D resistivity structures, vertical electrical soundings and the geo-electric sections delineated 3-layer subsurface models. Low resistivity topsoil (generally < 50 ohm-m) and composed of clayey soil within swampy environment was delineated. The weathered layer which underlies the topsoil, presumed to be clayey, is inundated by mostly extremely low resistivity with relatively thick column. The fresh basement, identified as the competent layer has its resistivity masked by the resistivity of the overlying strata; having low resistivity values possibly precipitated by the significant clay content and swamp environment.



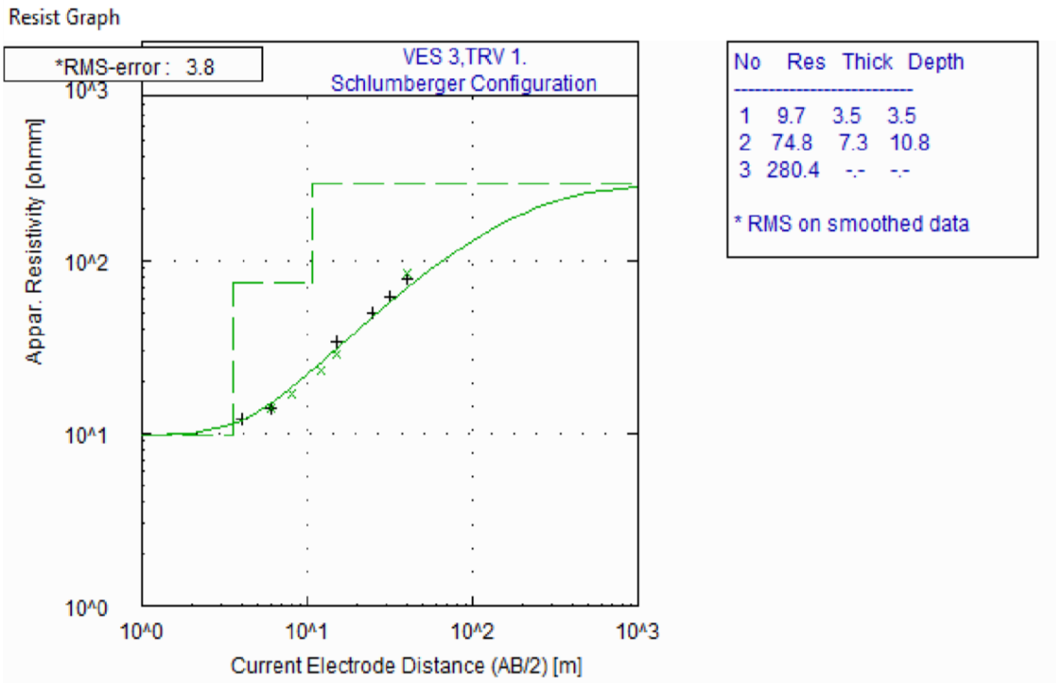


Figure 8: Typical H and A type curves from the study area

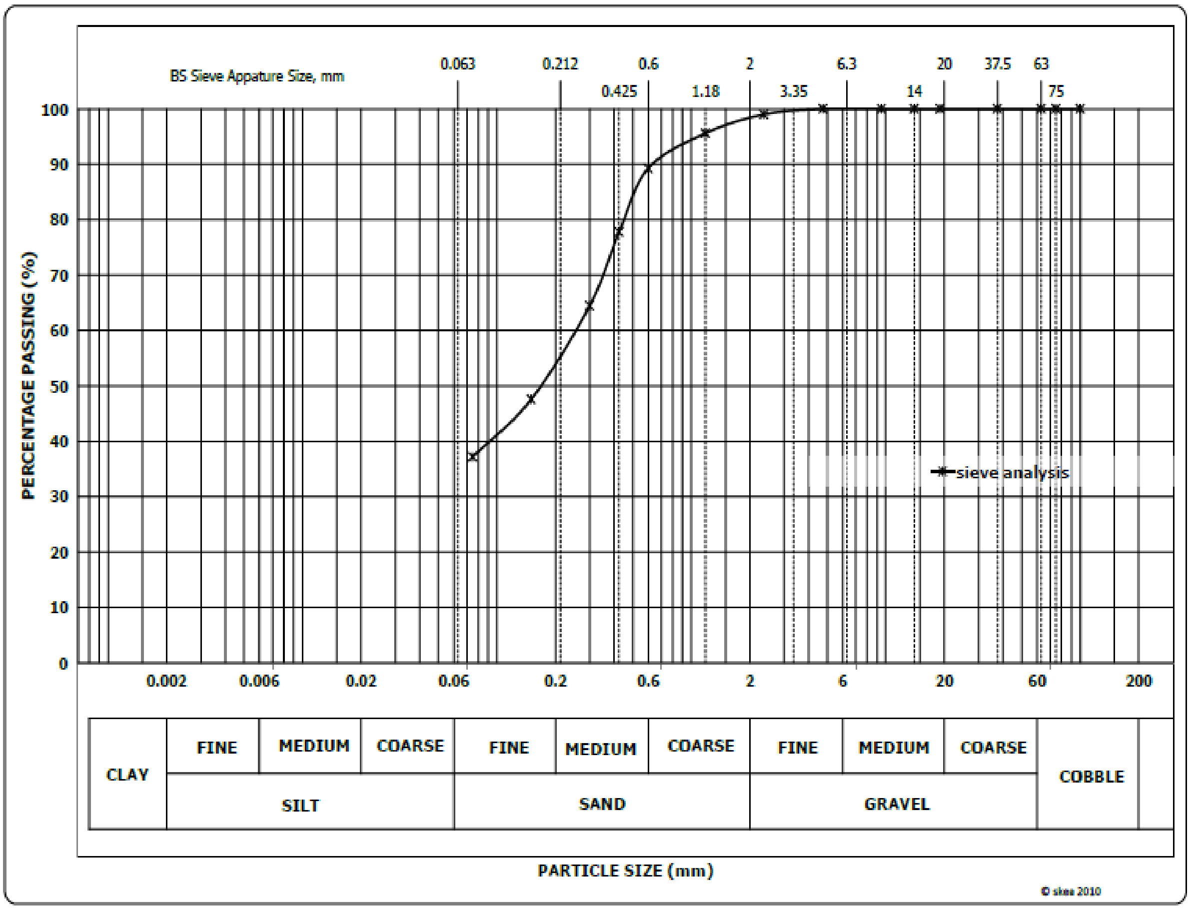


Figure 9: Particle size distribution graph for location 2

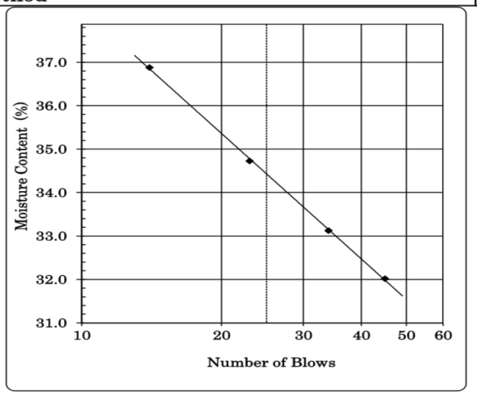
Table 1: Particle size distribution results for location 2

Particle size	Percentage (%)	Percentage of particle size (%)
Gravel	1.0	Gravel = 1.0
Coarse sand	9.7	Sand = 61.8
Medium sand	24.8	
Fine sand	27.3	
Clay/Silt	37.2	Clay/Silt = 37.2

L1 A

Casagrande method

LIQUID LIMIT, LL TEST			LL =	34.4 %
Test No.	1	2	3	4
Container No.	A	B	C	D
Wet Soil & Container g	33.15	32.71	33.95	32.99
Dry Soil & Container g	28.60	28.10	28.70	27.60
Container Empty g	14.40	14.20	13.60	13.00
Dry Soil g	14.20	13.90	15.10	14.60
Loss of Water g	4.55	4.61	5.25	5.39
Moisture Content %	32.04	33.14	34.75	36.90
Number of Blows	45	34	23	14



PLASTIC LIMIT, PL TEST		
Test No.	1	2
Container No.	A	B
Wet Soil & Container g	26.55	29.04
Dry Soil & Container g	24.40	26.70
Container Empty g	13.20	14.40
Dry Soil g	11.20	12.30
Loss of Water g	2.15	2.34
Moisture Content %	19.20	19.00
Plastic Limit, PL =	19.1 %	

LINEAR SHRINKAGE	
Original Length, L_o (mm)	140
Final Length, L_f (mm)	131
Linear Shrinkage = $(1-(L_f/L_o))*100$	6.4
Shrinkage limit =	11.0

Moisture Content Test		
Test No.	1	2
Container No.	A	B
Wet Soil & Container g	26.01	28.45
Dry Soil & Container g	24.40	26.70
Container Empty g	13.20	14.40
Dry Soil g	11.20	12.30
Loss of Water g	1.61	1.75
Moisture Content %	14.40	14.20
Moisture Content % =	14.3 %	

USCS GROUP SYMBOL:	(CL)
Plasticity Index	15.30

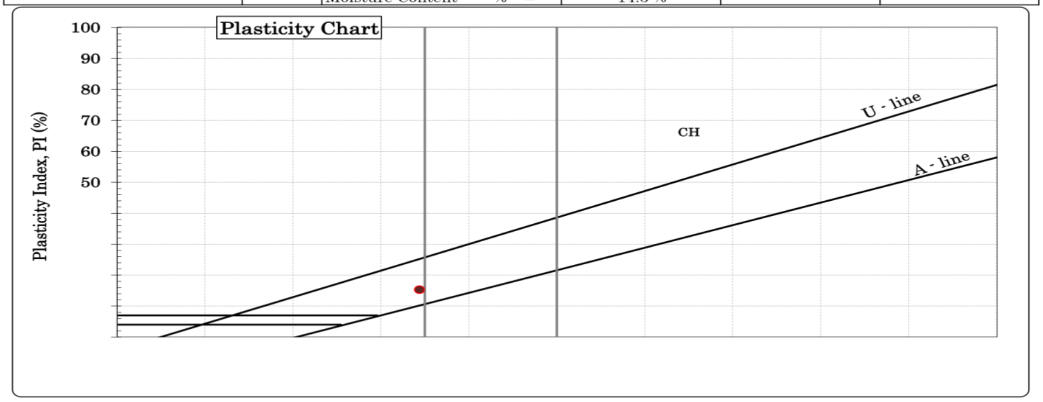


Figure 10: Atteberg limits chart (Liquid limit, Plastic limit and Plasticity index) for location 1

The geotechnical results show that the analyzed soil samples have generally high consistency limits; indicating high percentage of clay content in the soil. The liquid limit, plastic limit, shrinkage limit and plasticity index values range from 34 - 41%, 19 - 21%, 9.1 - 11.0% and 15 - 21% respectively; showing generally poor foundation materials of significant compressibility due to high clay content coupled with the swampy nature of the area. There is close inter-relationship and corroboration between the geophysical and geotechnical results, where relatively low resistivity parameters are often diagnostic of porous and unconsolidated soils or shear zones that could be inimical to stability of civil engineering structures.

The effectiveness of integrated geophysical and geotechnical investigation have been demonstrated through the delineation and identifying non-suitability of underlying foundation beds at a proposed site for engineering purpose. The study procedures are useful tools in making requisite recommendations that would guide civil engineers and building professionals to take futuristic safety decisions with consideration to site conditions and the building project. The study concluded that weak and low bearing materials constituted the subsoil layers considered not appropriate to support major engineering structure of significant dead load. However, deep foundation and good drainage system may suffice as part of other important professional decisions that could enhance the integrity of construction plans. In essence, building professionals could harness from research knowledge and build synergy with experience of geoscientists; thereby adding value to services in the construction industry.

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