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Uncertainties in Subsurface Characterisation For Building Construction: Case Studies of Two Site Investigations in Lagos Metropolis

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Abstract
Geotechnical frameworks and calculations rely on adequate characterisation of the subsurface soil units. Boring tests and their distribution provide, not only geotechnical parameters but also to reveal geotechnical units and lateral extent, which are particularly important for safe and cost-effective foundation design. This study presents two cases of geotechnical site investigation involving boring tests in two areas of Lagos metropolises that raised concerns about uncertainties in subsurface characterisation caused by the inadequacy of field techniques employed. This study revealed the limitation of geotechnical designs at A and B, largely due to the uncertainty of subsurface characterisation induced by inadequate quality and quantities of field tests. Using data from geotechnical boring (percussion drilling) and resistivity survey (2D tomography and VES), the occurrence of unusual ironstone was established between 9 to 15m depth at Site A, which prevented further drilling with a percussion rig. However, this ironstone occurrence is non-lateral as the resistivity obtained in 2D profiles ranges from 15 Ωm – 74 Ωm from the surface to 35 m, suggestive of Clay and Sand. Thereby complicating geotechnical design. Notably, one boring is grossly inadequate for characterising the complexity of the geology at Site A. Similarly, a forensic investigation at Site B indicates the inadequacy of one boring test since the correlation of results from three new borings revealed a complex geology which was missed using only one. Installed piles on this site were mostly seated on Organic Clay between 15 and 30m depth. Evidence presented in these case studies underscores the importance of comprehensive subsurface characterisation to enhance design decisions for geotechnical recommendations.

***Keywords**: Soil units; Boring test; Subsurface-uncertainty; Building; 2D Resistivity; VES; Subsurface-characterisation*

Introduction

Building collapses have become rampant and at an alarming rate in certain Lagos metropolis and across the nation recently, causing loss of human lives and economic drains (*Hamma-Adama & Kouider, 2017; Okeke et al., 2020; Awoyera et al., 2021*). Research has reported several underlying factors for this unfortunate occurrence, among which are related to the common use of substandard building materials, involvement of unskilled workers, disregard of existing building codes as well as incompetency of building foundations (*Oloyede et al., 2010; Akinyemi et al., 2016; Hamma-Adama & Kouider, 2017 Oyedele 2018*). Demographic data show that the human population is increasing globally, particularly in urban cities. Hence, the increase in construction works, pushing construction activities to areas previously abandoned spots of relatively poor subsoil condition. These areas often require surface soil stabilisation and some may require extremely deep foundation to support building size of proportionate economic values. However, in site investigation work, uncertainty in the geotechnical characterization of the subsoil condition due to human error can be enormous, particularly in areas with geological complexity such as deltaic and lagoonal depositional environments (*Chao et al., 2021; Shi and Wang, 2023;* Xue et al., 2024).

Advanced technology has enabled advanced global megacity to achieve 3D subsurface models with reliable accuracy for constructing surface and subsurface infrastructures (*De Rienzo et al., 2008; Pan et al., 2020; He et al., 2023*). As a stepping stone for Lagos state, with itsmegacity vision by 2030, this city needs reliable input from engineering geologists and other building/engineering professionals to lessenbuilding collapse associated with poor soil and foundation. Lagos is the smallest state in Nigeria by landmass and a major part of its land that remains undeveloped lies in coastal areas with poor soil and complex geological sedimentary deposition (*Oyedele et al., 2011; Faseki et al., 2016; Ubido et al., 2017*). A typical subsoil characterization for a field geotechnical survey requires two basic testing programs; penetration test and geotechnical borehole (percussion drilling). The common practice par building code for site investigation in Lagos state has a minimum requirement of two (2Nos) CPT and one (1No) geotechnical borehole for a plot of land. This minimum requirement is upheld by practitioners for both private and commercial properties. Often due to cost constraints, most practitioners cut down on this requirement. This practice has proven vital, resulting in foundation failure,

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especially in poor and complex geology in Lagos coastal terrain. The quality and quantity of geotechnical field programs ultimately to a large extent, determines the quality of subsurface characterization, especially in poor and complex geological terrain. This study presents two case studiesthat demonstrate the danger of possible high uncertainty associated with inappropriate quantity and quality of geotechnical field programs as related to foundation failure.

For the proprietary nature, the two sites are named Site A and Site B respectively. Site A is situated very close to the canal that drains across Site A metropolis, where a geotechnical borehole was abortive due to the occurrence of rare and unusual deep-seated ironstone. Thereby, suggestive of a misleading occurrence of adequate load-bearing stratum for possible pile foundation. Case 2 is a forensic investigation of a piled building under construction at Site B, experiencing punch-in failure due to an inadequate geotechnical field program.

Study Area

Site A and Site B are two Lagos metropolises unified based on the occurrence of poor subsoil and complex geology due to their proximity to major canals and proximity to the coastline as shown in Figure 1 above. Like most islands, islets, peninsulas and other landforms to the South of Lagos Mainland, these case studies are located within the old beach ridge, which runs approximately parallel to the Atlantic Coast (*Boboye & Nwosu, 2014)*. The ridge is made of recent deposits of loose sands, shelly and sometimes alternating with variable thickness of organic clays and carbonized vegetable matter *(Adediran, et al., 1991;Boboye & Nwosu, 2014)*. The sediments were deposited under littoral and lagoonal conditions and affect continuously shifting lagoon and sea beach patterns and the varying sedimentation conditions within the environment (*Boboye & Nwosu, 2014; Ogunleye et al., 2024*).

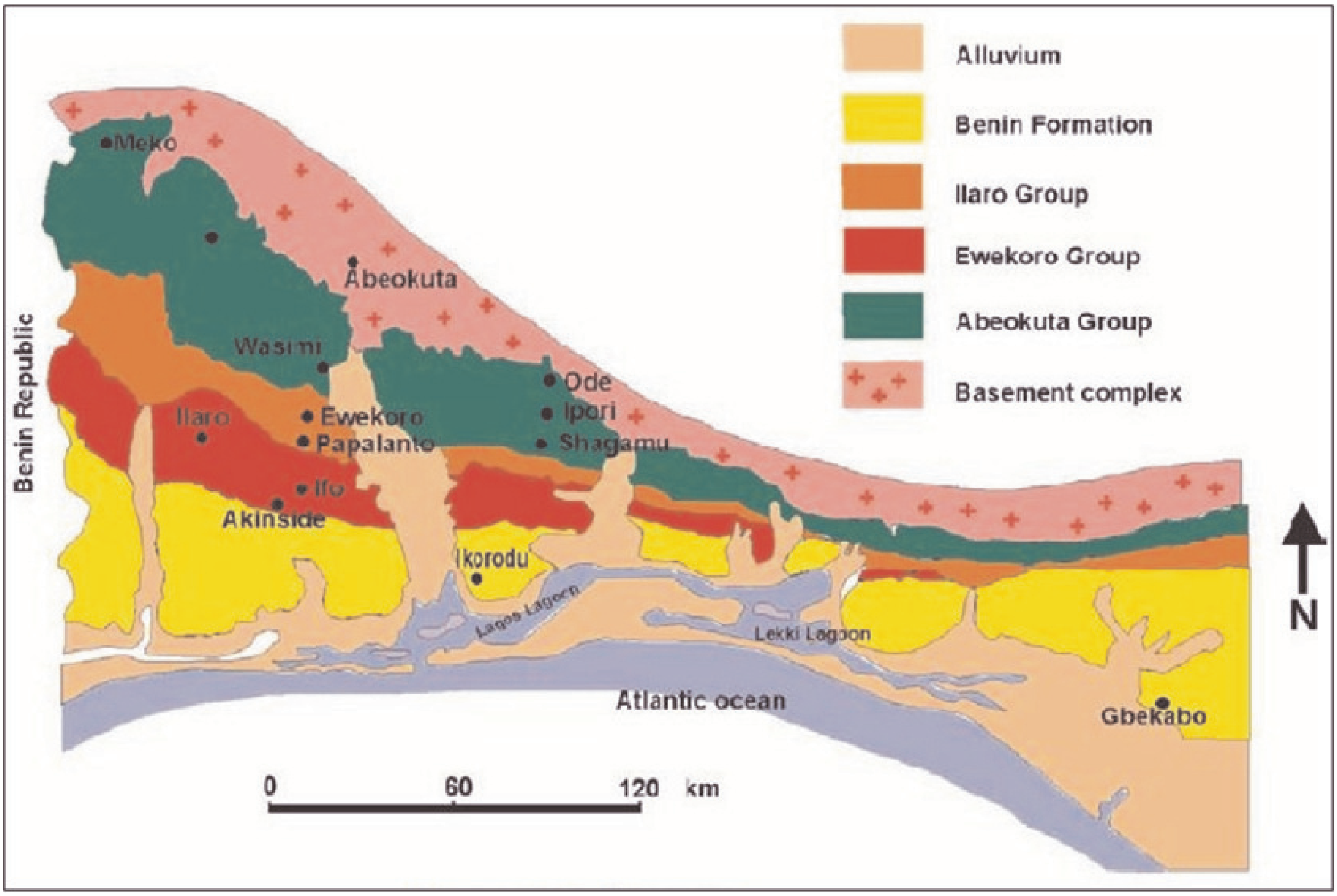

Fig. 1: Simplified Geological Map of South Western Nigeria.

Material and Methods

Boring tests with percussion drilling techniques were used to delineate soilunits for subsurface characterization in both case studies. However, a geophysical survey was used at Site A, to further characterize the geotechnical boring, to investigate possible lateral occurrence of the deep-seated ironstone that rendered the borehole test inconclusive. Two profile 2D resistivity survey and vertical electrical sounding were used for this purpose of delineation of the ironstone as shown in Figures 2 and 3 below.

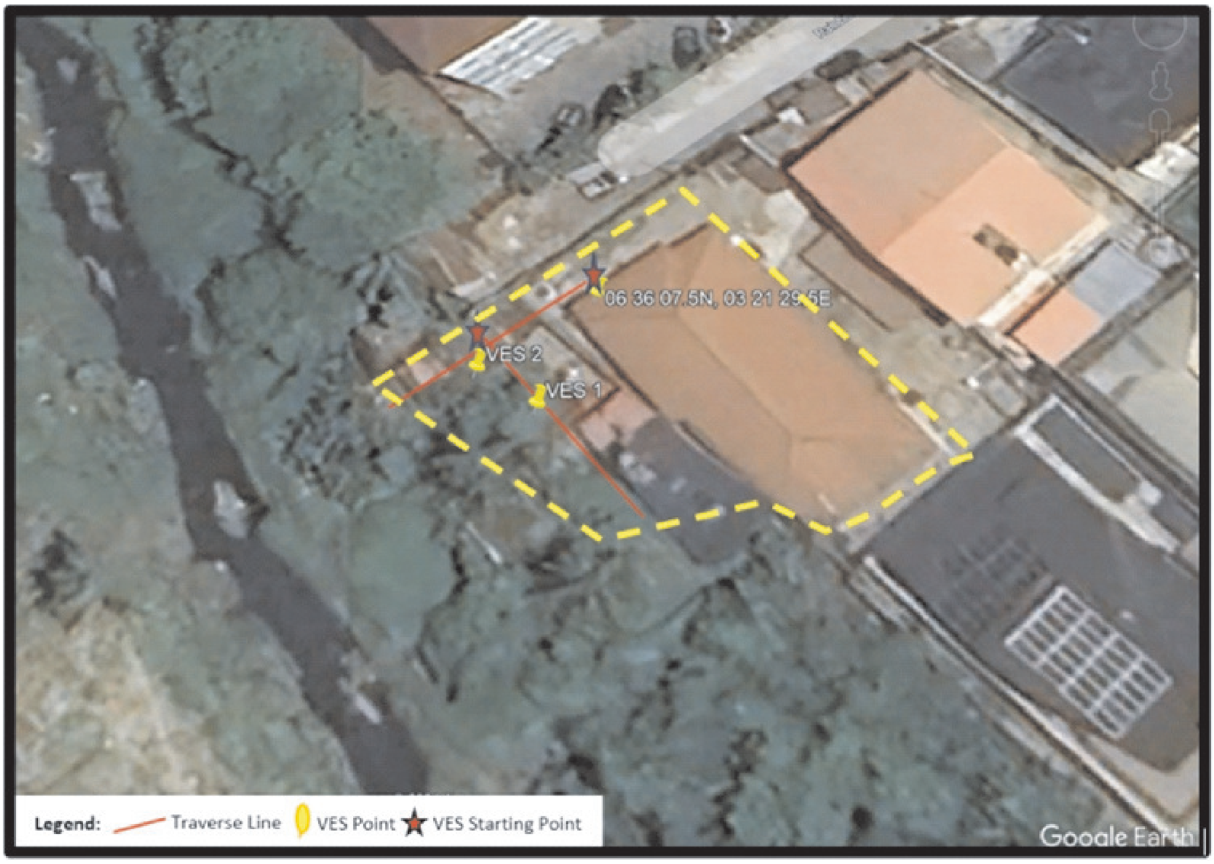

Fig. 2: Data Acquisition Map of the Study Area (Site A)

Geotechnical Borehole

Dando 150 percussion rig was used to drill the boreholes in both case studies. In the course of progressing the boreholes, sampling/testing procedures were undertaken broadly according to the procedures set out in BS 5930:1990 (Code of Practice for Site Investigation). Shell and auger boring tools (percussion) were used for progressing the borehole and SPT (Standard Penetration Tests) were carried out in cohesive soils at depth. SPT tests were carried out at 1.5m depth intervals in cohesionless soil where available. This test involves obtaining the number of blows (N-Values) producing the last 300 mm of penetration of the 50 mm OD split spoon sampler in connection with an overall 450 mm penetration test by 63.4 kg hammer free falling through 760 mm. However, no cohesionless material was encountered on the site at Site A. Ordinary disturbed samples were attempted as progress is made in the boreholes in such cases. Samples from the cutting shoe and split spoon barrel were collected as disturbed samples with respect to disturbed sampling and standard penetration testing. Undisturbed samples (U4) were attempted at the near-surface on both sites, to characterise the near-surface soil material for conventional shallow foundation options. Due to low consistency, near-surface samples were unrecoverable in cohesive soil on both sites. On the basis of the size of each study area and objectives, one borehole was carried out on Site A (site investigation), while three boreholes

Fig. 3: Data Acquisition Map of the Study Area (Site A)

Fig. 4: Distressed building on pile foundation (under construction) and distribution of boring test (Site B).

were carried out on Site B (forensic study). Figure 4 shows the location of the building under construction on Site B and the environs, characterised by swampy terrain.

Geophysical Survey

The Electrical resistivity method involves the passage of electrical current into the ground through two current electrodes while the potential drop is measured across another pair of electrodes which may or may not be within the current electrodes depending on the electrode configuration. The PASI resistivity meter was used for the data acquisition. The data acquisition was done by using two (2) different techniques which include 2-D electrical resistivity tomography and vertical electrical sounding.Figures2 and 3 respectively represent the data acquisition map of the area showing the 2-D traverses and VES points and a picture of data acquisition in progress at Site A.

2-D Electrical Resistivity Tomography (ERT)

The 2-D resistivity imaging was carried out along two (2) geophysical profiles with a maximum length of 35 m long. Dipole-Dipole array configuration with an inter-electrode spacing of 5 m was used. Dipro Software was used to obtain the 2D resistivity pseudo section which is a representative of the subsurface geoelectric and lithologic layer.

Vertical Electrical Sounding (VES)

The VES were carried out to furtherconfirm the geoelectric or lithologic layer identified from the 2-D ERT results. Two (2) points were sounded at the proposed site. The VES data were collected using the Schlumberger electrode array configuration and a maximum AB (m) of 40 m was achieved due to space limitation. Winresistsoftware was used to obtain the 1-D resistivity-sounding curves. However, the results obtained from the partial curve matching were used for constraining the interpretation with the software.

Results - Description of Soil Units

Study 1: Site A

Borehole

The borehole that was carried out on this site confirms complex subsoil layers soil types representing five (5) subsoil zones that typify lagoonal depositional environment (Figure 5). The subsoil characterization on this project site exhibits varieties of soil types including sandy clay fill material as topsoil, underlain by soft inorganic clay, firm to stiff light and mottled clay and deep-seated Ironstone. The upper zone of the subsoil of fill material comprises of sandy clay, which extends from the topsoil to about 3m depth. Between 3m depth to 6m, exist a very soft to soft inorganic Clay material. These two subsoil zones are deemed unsuitable for relatively moderate to heavy bearing loads. The occurrence of soft organic and inorganic clay at the near surface is particularly a limiting factor for the use of a shallow foundation on the project site. Attempts to take U4 samples at near surface (1.5 m, 3 m and 4.5 m) within the upper soft clay were abortive. This clay readily losesstrength when remolded due to its sensitivity. Between 6 m and 9.75 m is a firm to stiff light grey and mottled Clay (rust brown and light grey). U4 blow of 14 was recorded at 6.75 m depth in this subsoil layer. Beyond 9.75 m depth, Ironstone was encountered, which extent to the termination depth of the borehole test at 15 m.

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Geophysical

2D Resistivity Imaging

2D Resistivity Imaging along Traverse 1

Figure 6 represents the 2D resistivity imaging along profile 1. From the 2D resistivity pseudo-section, three (3) geoelectric layers were delineated which include the topsoil, peat/sandy clay and sand/sandy clay/clayey sand. The resistivity of the section varies between 15 Ωm – 74 Ωm and penetrates to depth of 35 m. The 2D result showed that the sandstone beneath the proposed site is not continuous and could terminate at depth below 25 m. The sandy clay/clayey sand was delineated toward the left-hand side of the pseudo section.

2D Resistivity Imaging along Traverse 2

Figure 7 represents the 2D resistivity imaging along profile 2. From the 2D resistivity pseudo-section, three (3) geoelectric layers were delineated which include the topsoil, peat and sand/sandy clay/clayey sand. The resistivity of the section varies between 27 Ωm – 79 Ωm and penetrated to depth of 21 m. The clay delineated as the second geoelectric section has resistivity values ranging from 27 Ωm – 36 Ωm extends from depth of

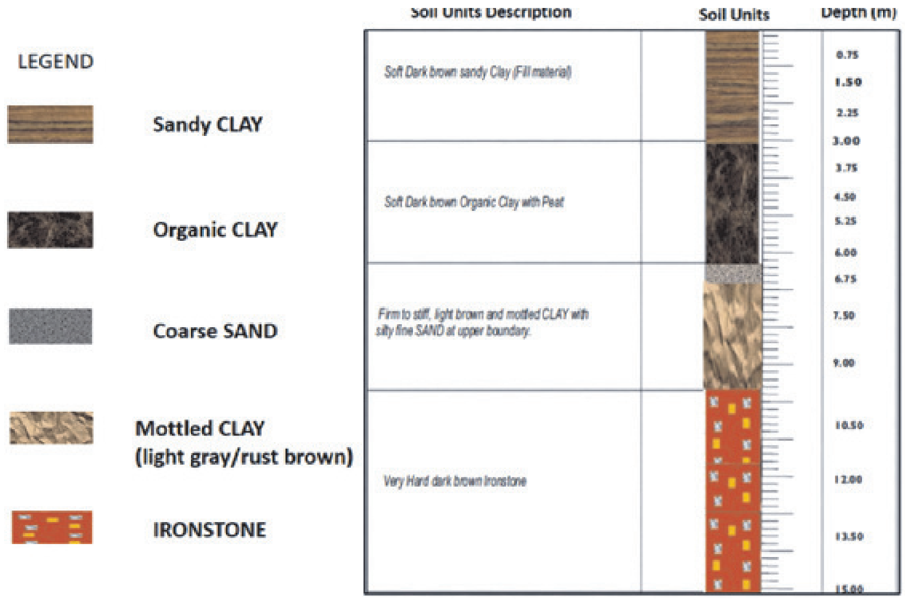

Fig. 5: Schematic representation of subsurface at Site A

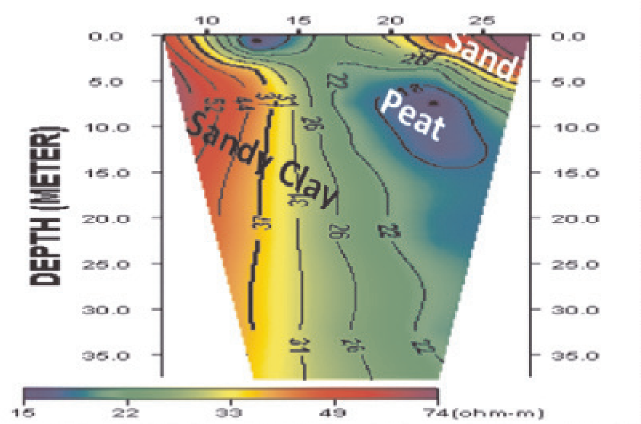

Fig. 6: 2D Resistivity Imaging across Profile 1

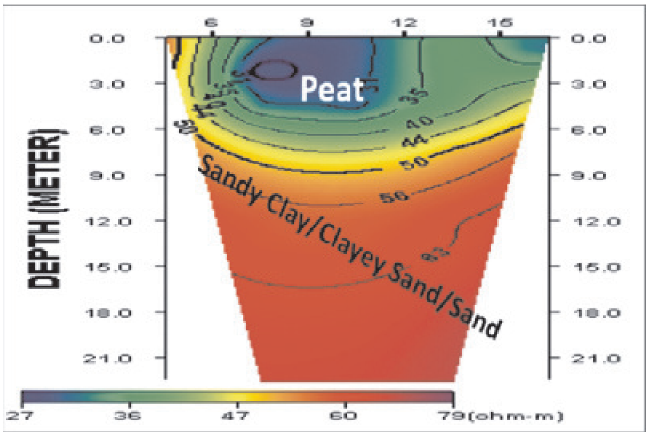

Fig. 7: 2D Resistivity Imaging across Profile 2

about 1 m – about 6 m. The 2D result showed that the clay was underlined by clayey sand/sandy clay and sand material. The clayey sand/sandy clay extends to depth of about 21 m. Thus, the 2D result does not show any continuity of any form of iron sandstone.

<u>*2D Vertical Electrical Sounding*</u>

The VES results are presented as 1-D resistivity sounding curves as showed in Figures 8 and 9. The curves were interpreted qualitatively and quantitatively. Quantitative interpretation of the curves involves partial curve matching using two layers Schlumberger master curves and the auxiliary K, Q, A and H curves. The qualitative interpretation reveals A curve type.

Case Study 2: Site B

The borehole that was carried out on this site revealed complex subsoil layers of soil types representing five (5) subsoil zones that typify the lagoonal depositional environment (Figure 10). The subsoil characterization on this project site exhibits varieties of soil types including sand sand fill material as topsoil, underlain by soft inorganic Clay, firm Organic Clay and upper loose Sand and deep-seated medium dense Sand layer. The upper zone of the subsoil of fill material comprises of sand used as fill material on the project site, which extended from the topsoil to about 3 m depth. Between 3m depth to 6 m, there is an occurrence of intercalation of Organic Clay (with peat), inorganic sandy Clay and Upper loose Sand. These subsoil materials have varying and inconsistent thicknesses across the project site.

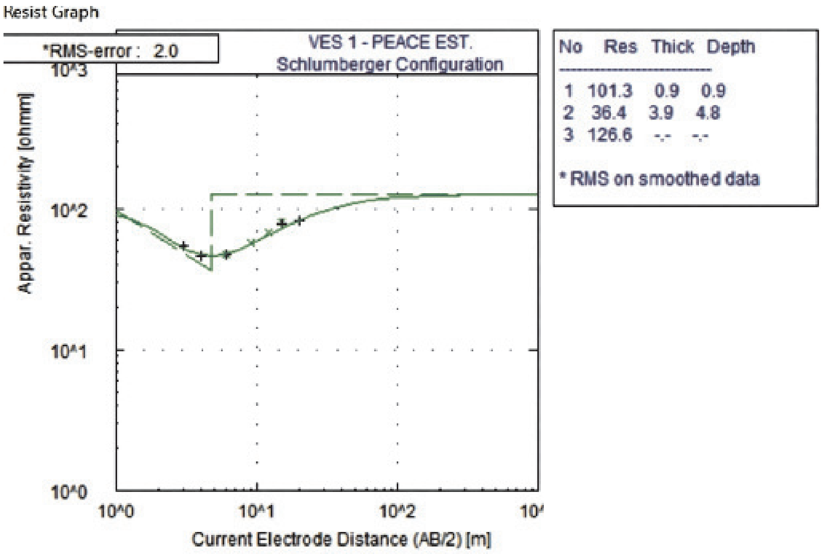

Fig. 8: Typical 1-D Resistivity Curve – VES 1.

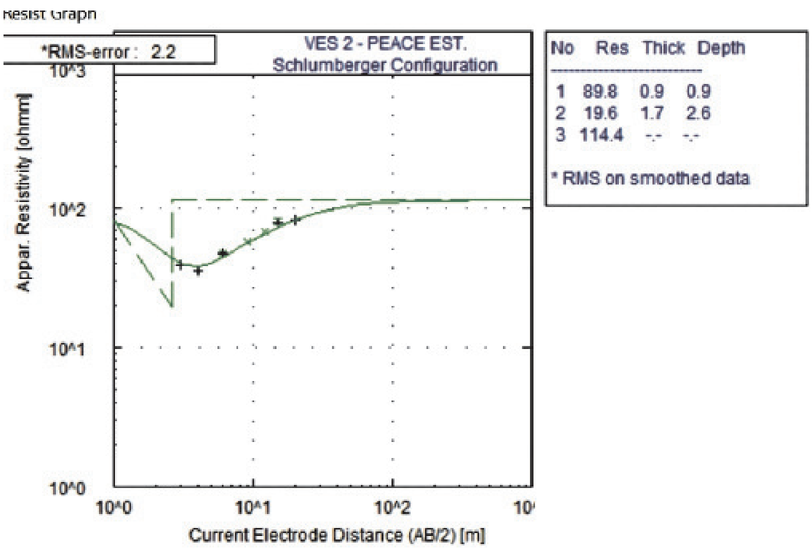

Fig. 9: Typical 1-D Resistivity Curve – VES 2.

Both inorganic Clay and the Organic Clay are soft to firm in consistency. Clay is not a good foundation medium. Since the upper Sand is loose in relative density and also does not have consistent thickness across the project site, thus, deemed unsuitable to support a relatively moderate bearing load presently on the project site. Generally across the project site, there is an extensive occurrence of soft/firm organic Clay from 16.50 m to about 29 m depth. U4 blow record ranges between 8 and 13, suggesting soft to firm in consistency. Beyond 30m depth, a deep Sand layer was encountered, which extent to the termination depth of 40 m in the borehole tests. N values obtained within this sandy subsoil range between 12 and 32, indicative of medium dense to dense Sand in relative density. This sand layer is predominantly fine, medium and coarse particles with occasional gravel, according to BS 5930:1990 (Code of Practice for Site Investigation). This Sand is the only nearest (in depth) competent layer suitable to support a moderate/heavy bearing load on this project site via pile foundation.

Discussion of Results

The effect of common practice involving one boring test for subsoil characterization in the geotechnical survey is here discussed as revealed by this study. The result from one boring test at Site A returned inconclusive for determination of depth to suitable stratum for pile foundation due to the occurrence of

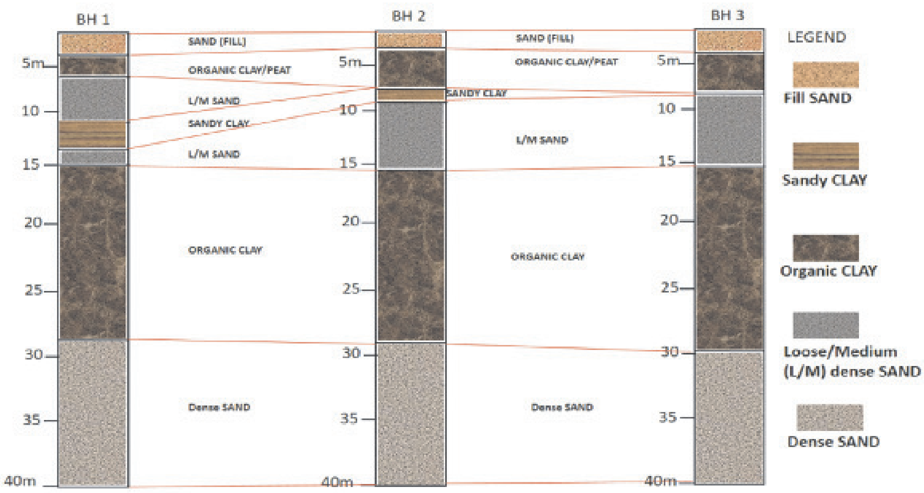

Fig. 10: Schematic representation of the subsurface at Site B

unusual ironstone formation. This ironstone was encountered from 9 m to 15 m depth. Further drilling with a percussion drilling rig became difficult as the impact of the iron stone on the drilling shell was high, leading to noticeable damage to the machine and accessories. 2D resistivity tomography and VES agreed with the soil units delineated by the boring test. The resistivity of the two 2D sections varies between 15 Ωm – 74 Ωm between the surface materials were obtained to 35m depth. Therefore, the relative increase in resistivity beyond 15 m depth does not suggest a lateral occurrence of the ironstone encountered in the subsoil. Hence, the occurrence of this unusual deep-seated ironstone complicates geotechnical design on this site. Generally, ironstone is not among the common sedimentary facies often reported in near-surface geotechnical boring in this part of Lagos metropolis. Especially not at deeper depth, underlying lagoonal deposit. However, this ironstone could be associated with MaastricthianOwelli-Ajali continentally derived ferruginous sand and clay deposit within Dahomey (*Adediran et al., 1991*). Since it is non-lateral, this ironstone should not be mistaken for an adequate stratum for a load-bearing pile. A comprehensive geotechnical survey is therefore required to adequately characterise the subsoil for informed geotechnical design.

Similarly, in the forensic study of a failing pile foundation on a building at Site B, piles were terminated at 12-15 m depth on account of a geotechnical study that relied only on one boring test. Results presented in this study (section 4.2) however revealed a complex geology that cannot be characterised with one boring test. The result obtained from three (3) boring tests that were carried out for the forensic investigation as shown in Figure 10, confirmed the complexity of the subsurface soil units in terms of varying thickness and difference in corresponding depth of occurrence of soil units. Most notable is the observed occurrence of organic Clay at/near 12-15 m depth, which explained the reason for punch-in failure noticed on the buildings supported by these piles. The Sand layer targeted as a support for the existing piles does not have a lateral extend across the entire site, due to the complexity of geology in the terrain. Going by the subsurface characterization with the three (3) new boring tests, pile depth on this site should not be placed at any depth above 30m at the least.

Conclusion

The effect of incomprehensive geotechnical survey in areas of complex geology is presented with two case studies. At Site A, the occurrence of deep-seated ironstone is significantly a new finding within common sediment characterized in Lagos depositional facies. And it is thought to be associated with Maastricthian Owelli-Ajali continentally derived ferruginuous sand and Clay *(Adediran, et al., 1991*). The resistivity survey revealed the non-lateral occurrence of ironstone. Therefore, the existence of this subsoil ironstone should not be mistaken for an adequate stratum for load-bearing in construction works. Similarly, geotechnical subsoil characterization at Site B revealed a need for adequate quantity and quality of field boring tests. Using one boring test presented a gross error, resulting in punch-in failure of piles under an existing building. With the use of three (3) boreholes, a complex geology was revealed on this site, with varying thicknesses and differences in the corresponding depth of occurrence of soil units. This simple measure can substantially improve foundation design, to avoid unnecessary building collapse.

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