Geoelectrical-Geotechnical Studies for Near Surface Characterization, Case History: Lagos, SW Nigeria

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ABSTRACT

Incessant building collapse and foundation failures in Nigeria have continued unabated in recent years, causing loss of lives and properties worth hundreds of thousands of US dollars. This research in Gioni estate Lakowe, Lekki-Epe, Lagos, Nigeria is concerned with an integrated characterization of near-subsurface geomaterials using geoelectrical resistivity tomography and geotechnical techniques as part of the preliminary investigations for foundations studies and other building construction projects. Four traverses of the geoelectrical resistivity measurements using Wenner array configuration were conducted, and cone penetrating data were equally obtained along the same traverse. A borehole data point was equally acquired for ground thruthing. Based on their geoelectrical properties, three lithologies including loose sand, compacted clayey sand and clay/peat units were delineated with apparent resistivity values ranging 50 – 260 Ωm, 20 – 72.2 Ωm and $\leq$ 27.5 Ωm respectively. Average Cone penetrometer (CPT) value was about 110 kg/cm^2 with an average SPT ‘N’ value of 25, indicating that the soil material is of good geotechnical properties. Laboratory tests conducted on the representative soil specimen at 3.75 m depth revealed moisture content (MC) of 66% which can be attributed to the clay contents. The Liquid Limit (W_L), Plastic Limit (W_P) and Plasticity Index (PI) tests results gives 84%, 30% and 54% respectively. The choice of deep seated foundation such as pile foundation is considered a better alternative to shallow foundation for proposed buildings in the study area where higher loadings are anticipated to transmit the loads to a stable soil layer.

KEYWORDS: Geophysical investigation; Geotechnical engineering; Subsoil investigations; Foundation failures.

INTRODUCTION

Near surface investigation and characterization phase prior to every construction have become an essential component to ensure safety of human lives and properties, where there are inadequate or inefficient subsoil characterization and soil strength determination, a potential foundation-related failures or structural dilapidations may result. The prime purpose of detailed geological and geoengineering subsurface investigations is to design earthworks and foundations for structures, and to execute earthwork repairs necessitated by changes in subsurface environment. These investigations usually include surface and subsurface characterization, soil sampling and laboratory analysis. There have been several incessant building collapse and foundation failures in Lagos, southwestern Nigeria in recent years causing loss of lives and properties. The cause of these tragedies has been linked to many factors by the engineering community, among which are, bad design, faulty construction, overloading, non-possession of approved drawings, non-compliance with approved drawings, and the used of quarks. It is quite unfortunate that subsurface conditions have rarely received due consideration prior to building construction. However, since all engineering structure is seated on earth materials, it is important to conduct pre-construction subsurface investigations of any proposed site in order to ascertain the strength and the competence of the subsoil earth materials.

Geoelectrical resistivity survey is the most common geophysical method used for site geotechnical investigation (Gowd, 2004). Various authors in literatures have integrated electrical resistivity and geotechnical data for characterization of the subsurface (Cosenza et al., 2006; Gay et al., 2006; Sudha et al., 2009). Apparent soil electrical conductivity (or resistivity) is influenced by a combination of several physico-chemical properties among which are clay content and mineralogy, soil water content, organic matter, and bulk density. Clay content can affect both strength and resistivity of the soil matrix in different degree. The ion exchange property of clay forms a mobile cloud of ions around each clay particle. These ions facilitate easy flow of electrical current within the clay matrix. Therefore, in fine grained soils like clay, the values of the electrical resistivity is usually lower than expected on the basis of chemical analysis of water extracted from soil (Zhdanov and Keller, 1994). Electrical resistivity tomography (ERT) measurements provide faster and comparatively cheap electrical imaging of the subsoil, thereby becoming an essential tool for geoelectrical characterization of soil. A full review on the application of electrical resistivity for subsoil characterization was conducted by Samouellian et al., 2005.

Alternatively, in geotechnical investigations, Standard Penetration Test (SPT) provides data regarding the soils' resistance to penetration in relation to the soil strength in terms of number of blows (N-values). The N-values are referred to as the number of blows per 30 cm of penetration into the soil and following the procedure of IS 6403-(1981) code, they can be used to estimate the bearing capacity of soils. The geotechnical dataset comprising of SPT and CPT, when integrated with the borehole data and laboratory tests of soil properties (e.g. grain size distribution, degree of saturation and permeability) can be used to characterize the subsurface soil. The main thrust of this research within the Gioni homes estate, Lakowe along Ibeju Lekki – Epe express way Lagos, is to delineate the near surface lithologies via geoelectrical resistivity imaging; conducting geotechnical analysis of soil samples in order to evaluate their index and engineering properties using in-situ borehole measurements and cone penetrating tests.

GEOLOGICAL SETTING

Lakowe is situated in the southeastern part of Lagos state, Nigeria, lying between latitude 06^0 26' 51.36" and 06^0 27' 04.32" N and longitude 03^0 44' 25.46" and 03^0 44' 51.36" (Fig. 1) within the southwestern Nigeria coastal zone, a zone characterized by coastal creeks and lagoons (Longe et al., 1987) developed by barrier beaches associated with sand deposition (Hill and Webb, 1958). Adegoke et al. (1980) recognized the abandoned beach ridge complex, coastal creeks and lagoons, swamp flats, forested river floodplain and active barrier beach complex as the five geomorphologic sub-units in the coastal landscape. Lagos is underlain by the eastern part of the Dahomey Basin (Fig. 2) with lithologic constituents that are mainly sands, clays and limestones (Nwankwoala, 2011). This section of the Dahomey basin is separated from the Niger Delta in the Eastern section by the Benin Hinge Line and Okitipupa Ridge and marks the continental extension of the chain fracture zone (Onuoha, 1999). The rocks are generally Late Cretaceous to Early Tertiary in age (Okosun 1990; Billman, 1992; Olabode, 2006).

The stratigraphy of the Dahomey basin as presented in Fig. 2 has been grouped into six lithostratigraphic formations namely, from oldest to youngest, Abeokuta, Ewekoro, Akinbo, Oshosun, Ilaro, and Benin Formations. Cretaceous Abeokuta Formation were later regarded as a group consisting of Ise, Afowo, and Araromi Formations. Tertiary Ewekoro Formation comprising of limestone, clays and shales, while the Ilaro Formation is predominantly clays and shales overlaid by the poorly sorted coastal plain sand units and Recent alluvial deposits. The surficial local geology of the study area in this research is that of Benin Formation (Miocene to Recent), recent littoral alluvial, lagoons and coastal plain sand deposits. The sand units within this part of southwestern Nigeria range in size from coarse to medium grained clean white loose sandy soil which graded into one another towards the lagoons and near the mouth of the larger rivers.

METHODOLOGY

The methods adopted in this research comprise of geoelectrical investigations using electrical resistivity imaging (ERI) technique and geotechnical tests, which include SPT, CPT tests and grain size distribution analysis of soil samples. Due to the non-uniqueness of geoelectrical resistivity inversions, borehole data were equally used to calibrate and constrain the geoelectrical resistivity data within the acceptable limits for subsurface lithological stratification. The details of each method of investigations are discussed in the following:

Geo-electrical investigations

2D geoelectrical resistivity imaging surveys were conducted using Wenner arrays electrode configurations (Fig. 3). The data were manually along the four traverses (P1-P4) as shown in Figure 4 using ABEM Terameter (SAS 1000/4000 Series). Traverses P1, P3 and P4 have profile length of 150 m while P2 has 100 m profile length due to limited space. All the four traverses were conducted along west-east direction.

The n-factor of the Wenner array configuration is the ratio of the profile length to the minimum electrode spacing; thereby making the total number of the electrode positions to be n+1

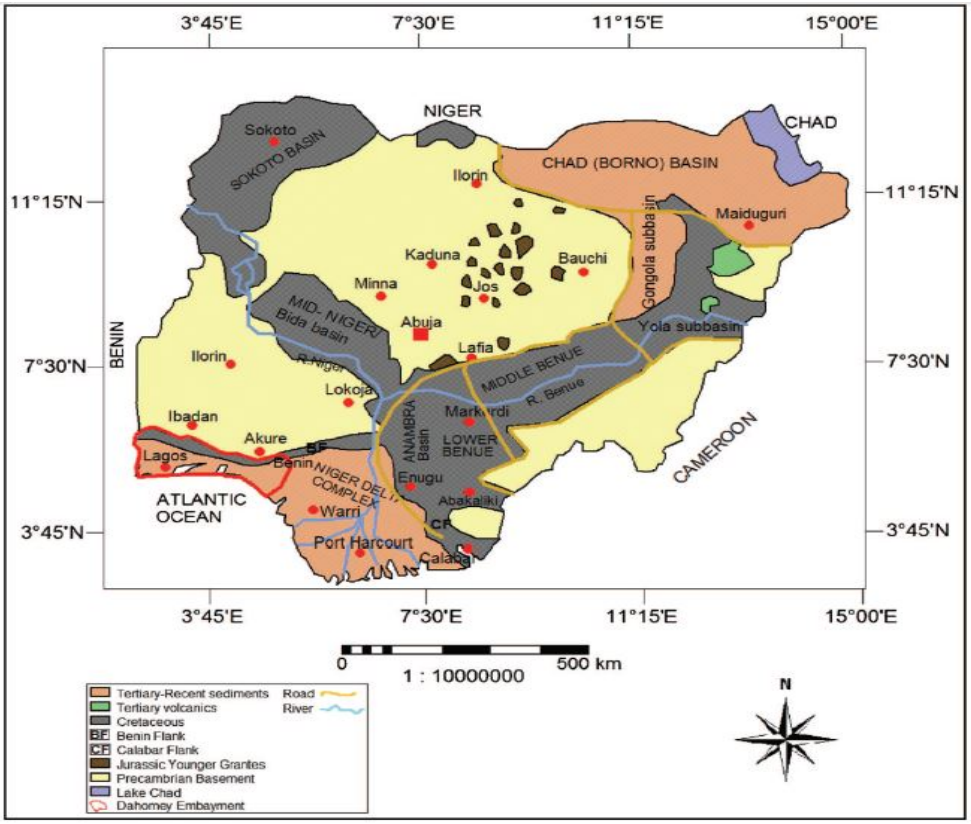


Figure 1: Geologic map of Nigeria showing the Dahomey Embayment

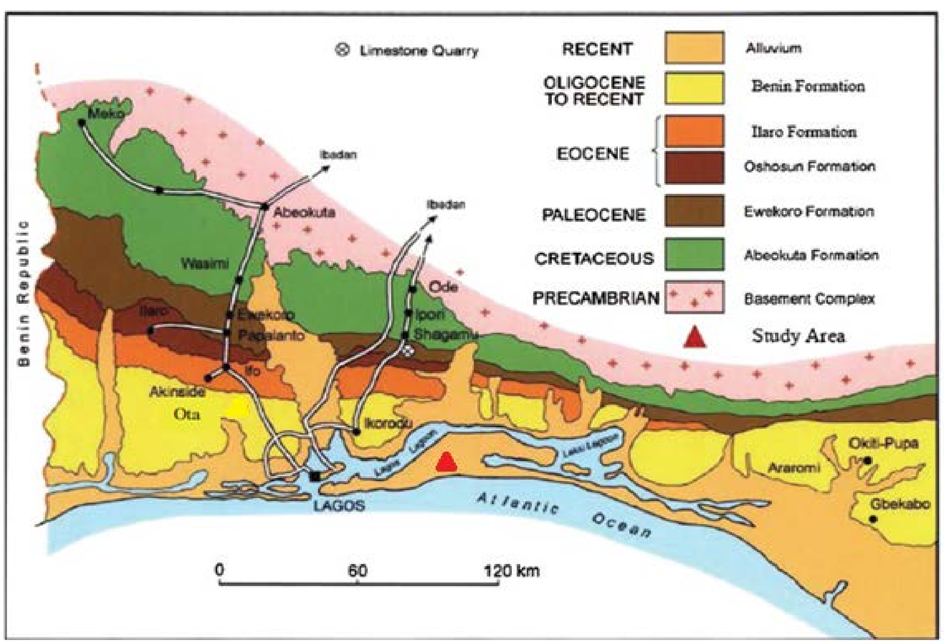


Figure 2: Geological map of the Nigerian part of the Dahomey embayment (modified after Gebhardt et al. 2010).

and maximum number of potential measurements for a given minimum electrode spacing “a” to be n-2. In this research, the minimum electrode spacing of 5.0 m was used for data measurements, and a data level of 9 (maximum electrode spacing of 45.0 m) was achieved in each of the profiles. Thus 144 data points were obtained for each traverse except P2. Special caution were taking in order to minimize electrode position error during the manual data acquisition; all electrodes were also maintained to have good contacts with the ground. A cycle of 4 was used for data stacking during the data measurements and the root-mean-square error for the acquired apparent resistivity data were maintained as <0.5%.

The observed apparent resistivity data for the electrical resistivity imaging (ERI) profiles were processed and inverted using RES2DINV inversion code (Loke and Barker 1996). This computer program employs non-linear optimization technique, which automatically determines 2D resistivity inversion model of the subsurface for the measured data (Griffiths and baker, 1993; Loke and Baker 1996; Aizebeokhai and Oyeyemi, 2014).

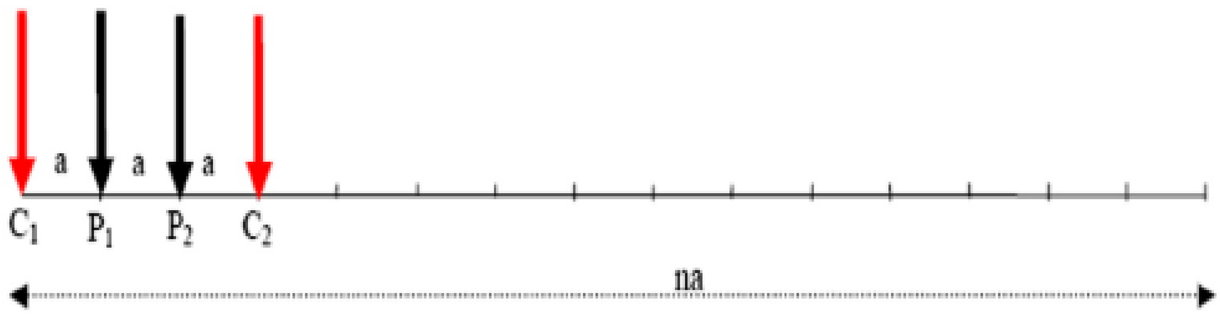


Figure 3: Electrode configuration for Wenner array

The subsurface is being subdivided into several number of rectangular blocks by RES2DINV code based on the spread of the measured apparent resistivity data, as determined by the survey parameters consisting electrode configuration, electrode separations and positions, and data level. Least square inversion technique was used to invert the 2D ERI data, and smoothness constraints which model the perturbation vector was applied. The quality of the generated inverse resistivity model for each traverse line was checked by monitoring the absolute error (ρ_{rms}) between the measured and predicted apparent resistivity data given by:

$$\rho_{rms} = \sum_{i=1}^{N} \left[\frac{\left| \log(\rho_{a_{meas}}) - \log(\rho_{a_{calc}}) \right|}{N} \right] \quad (1)$$

where $\rho_{a_{meas}}$ and $\rho_{a_{calc}}$ are the measured and calculated apparent resistivity values at ith data point respectively and N is the total number of data points.

Boring and Cone Penetrometer

The subsoil investigation was designed in accordance to the code of practice for site investigation BS 5930 (1999) to determine the geotechnical engineering properties of the subsoil condition within the study area. The investigation comprises of four (4) Nos. Dutch cone penetrometer test (CPT) denoted as CPT1, CPT2, CPT3 and CPT4 using a 2.5 Tonne capacity penetrometer machine and one (1) No. shell and auger borehole designated as BH1 was drilled to

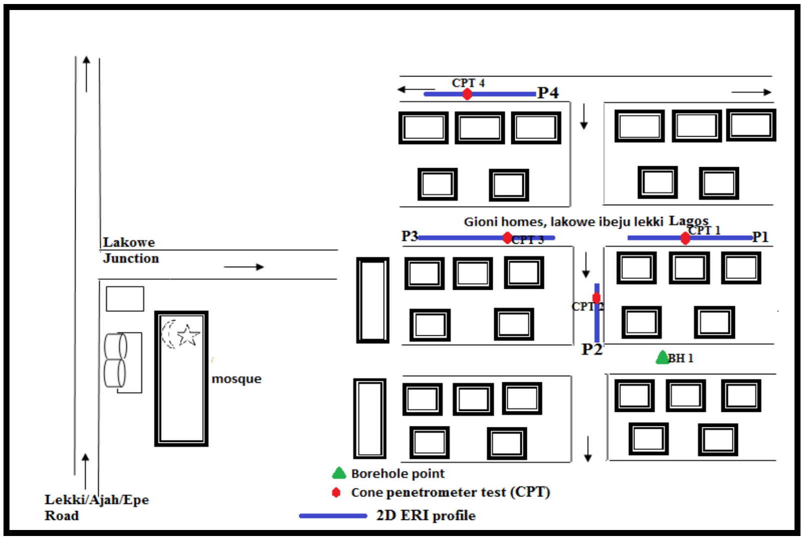


Figure 4: Basemap showing the location of study

30 m depths using a Dando percussion boring rig. The penetrometer tests were terminated at depths ranging from 8.0 m to about 11.0 m due to high resistance to penetrate further into the soil. All depths referred to are below the ground level at the time of investigation.

In the course of boring the following sampling procedures was adopted; disturbed samples were collected at depths of 0.75 m intervals and also at every obvious change of strata or convenient intervals for strata identification purposes through visual inspection and classification tests. Standard penetration tests (indicated as 'SPT') were carried out at every 1.50 m intervals to determine the relative densities in cohesionless strata. The tests were performed by driven a split spoon sampler of 5 cm diameter through the cohesionless strata and obtaining the number of blows (N-values) producing the last 30 cm of penetration in connection with an overall 45 cm penetration test by a 63.5kg hammer having a free fall through 76 cm. The required number of blows (N-value) to effect the last 30 cm penetration provide an indication on the relative density of the stratum tested.

Laboratory testing

All laboratory tests including moisture contents, sieve analysis and Atterberg limits were carried out in accordance with procedures specified in the BS specification method of testing soils for civil engineering purposes (BS 1377, 1990). Samples recovered from the borehole were carefully preserved and subjected to more detailed visual inspection. Representative samples were then selected from each stratum and subjected to classification tests for purposes of strata identification and classification. The moisture content of selected representative soil samples from each stratum were determined by finding the ratio of the weight of water in the soil sample to the dry weight of the soil sample. The moisture content is expressed in percentage.

Sieve analysis was carried out on representative soil samples to determine the particle size distribution of the soil. An approximately 500g weighed sample used for the test was washed using No. 200 sieve (0.075 mm) to separate the silt-clay and sand. The retained fraction on the sieve was then dried and subjected to sieving procedures by mechanical method using automatic sieve shaker and sieving, retained sample in each sieve is weighed. The consistency of the soil specimens with particle size less than 0.425 mm are determined by the Atterberg limit tests. These test indicate the plastic state of the representative soil samples in terms of the liquid limit (W_L), plastic limit (P_L) and plasticity index (PI) of fine-grained soil expressed as water content in percent. Reference standard: BS 1377 (1990).

RESULTS AND DISCUSSION

Subsoil Characterization

Geoelectrical resistivity survey revealed predominantly the presence of four geoelectrical layers across all the traverses (Figs. 5–7): topsoil which are predominantly loose sand unit with apparent resistivity values ranging 50 – 260 Ωm, compacted sand units with clay intercalations (20 – 72.2 Ωm); clay/peat layer with range of the apparent resistivity values $\leq$ 27.5 Ωm. The topmost loose sand layer with a consistent thickness of 13.5 meters across all the profiles, appears to be the materials used in sand-filling the area prior to building construction of the estate. This layer overlie conformably a more compacted clayey sand layer up to the depth of approximately 17.3 – 20 meters. The basal layer in the study area is a very low resistive clay or peat lithological unit.

The subsoil conditions as shown in soil borehole log (Table 1) revealed the near surface soil to be loose brown silty fine-medium grained sand with occasional fine gravel in places, underlain by organic silty sandy clay. Beneath the weak layer is medium dense coarse-medium fine grained sand with fine gravel in places to depth of boring of 30 m. The site investigation reveal that the soil deposit in the study area is predominantly cohesionless soil and the results from the SPT 'N' value coupled with the CPT result is significant in determining the relative strength of the strata. Table 2 presented the approximate relationship between the relative density, average SPT 'N' value, average Cone penetrometer (CPT) results and angle of internal friction (°) according to Meyerhof (1965). It clearly indicate that the near surface soil material is of loose relative density, soft consistency and high compressibility potential. It indicate that very limited magnitude of structural loading can be supported by the near surface in-situ soil materials. The curves of the SPT 'N' value and CPT results are presented in Fig. 8, which confirmed that the near surface soil material is of poor geotechnical properties, low shear strength and has high compressibility potential. Average Cone penetrometer (CPT) value gives about 30 kg/cm^2 with an average SPT 'N' value of 5. However, the soil materials underlying the weak stratum to depth of boring of 30 m is of medium relative density and shear strength. The soil material has a low compressibility potential. Average Cone penetrometer (CPT) value gives about 110 kg/cm^2 with an average SPT 'N' value of 25 as presented in Fig. 8. This indicate that the soil material is of good geotechnical properties.

A summary of the laboratory test results conducted on representative soil specimens obtained from samples collected from the borehole is presented in Table 3. The average moisture content (MC) is about 15%. However, the representative soil specimen at 3.75 m depth gives a moisture content (MC) of 66% which can be attributed to the clay content. The Liquid Limit (W_L), Plastic Limit (W_P) and Plasticity Index (PI) tests result on representative specimen gives 84%, 30% and

54% respectively. The obtained result indicate that the soil material is of medium plasticity. Table 4 shows the particle size distribution statistics for the non-plastic soil materials and classification according to the unified soil classification system. Figs. 9 and 10 presented the particle size distribution curves for the cohesionless soil materials at various depth intervals. The sieve result shows that the soil materials from 1.50 – 18.0 m depth is a poorly graded sand (SP) according to the unified soil classification system while the soil material from 18.0 – 30.0 m depth is a well graded sand (SW).

Implications for foundation studies

The results of the geoelectrical resistivity characterization of the subsurface revealed the presence of a competent layer inform of compacted clayey sand unit down to the depth of about 20 meters. Also the delineated clay units in the study area are unexpansive and may not compromise the integrity of building foundations in the area. Furthermore, the subsoil condition revealed through the boring log and penetrometer plots shows that the near surface soil is 2 m thick of loose silty sand. And underlying this near surface silty sand stratum is a formation of soft silty clay down to depth of about 7 m. The loose relative density/soft consistency and high compressibility potential of the near surface soil materials coupled with the high groundwater table encountered at about 1.50 m below ground surface indicate that limited magnitude of structural loading from the proposed building can be supported by the near surface in-situ soil materials using conventional near surface shallow foundation such as rafts so as to allow for foundation settlement to be within the tolerable acceptable limit. Moreover, the soil material that underlain the clay layer to depth of boring is medium dense sand. It is however suggested that where higher loadings are expected to be exerted on the soil from the proposed building, then it will be necessary to avoid the weak material stratum of soft clay by employing pile foundation to transmit the building load to the underlying medium dense sand stratum.

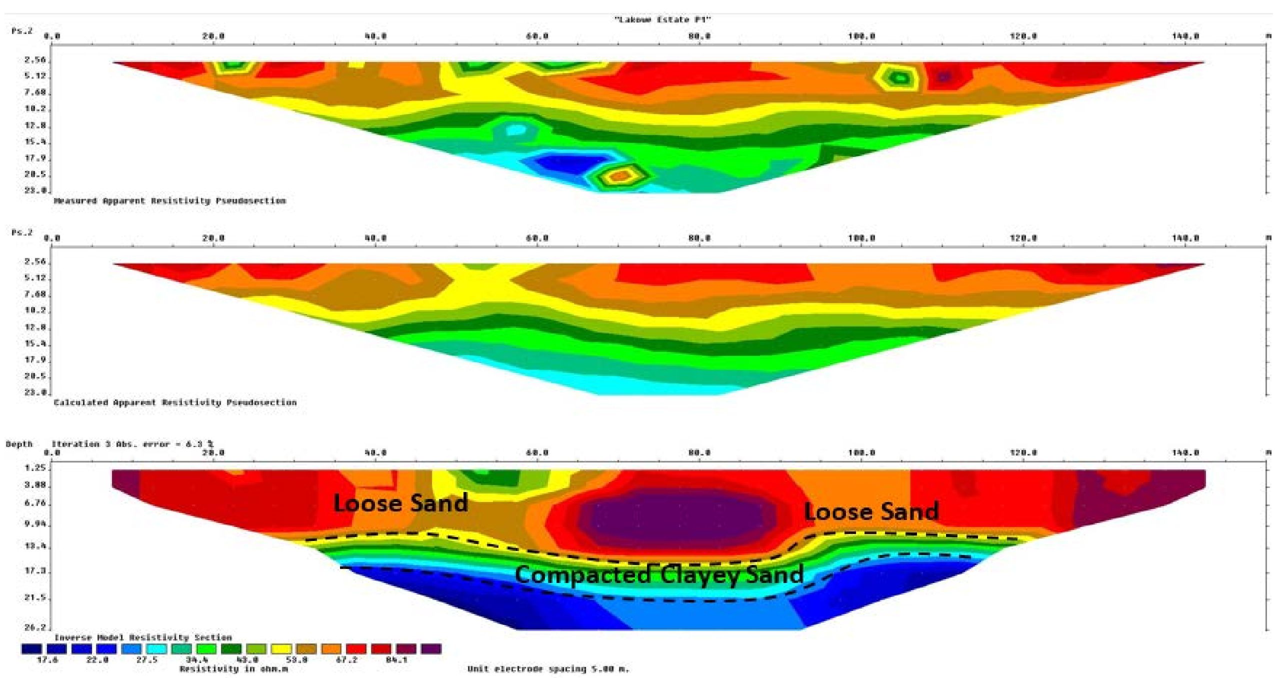


Figure 5: Inverse resistivity model of traverse P1

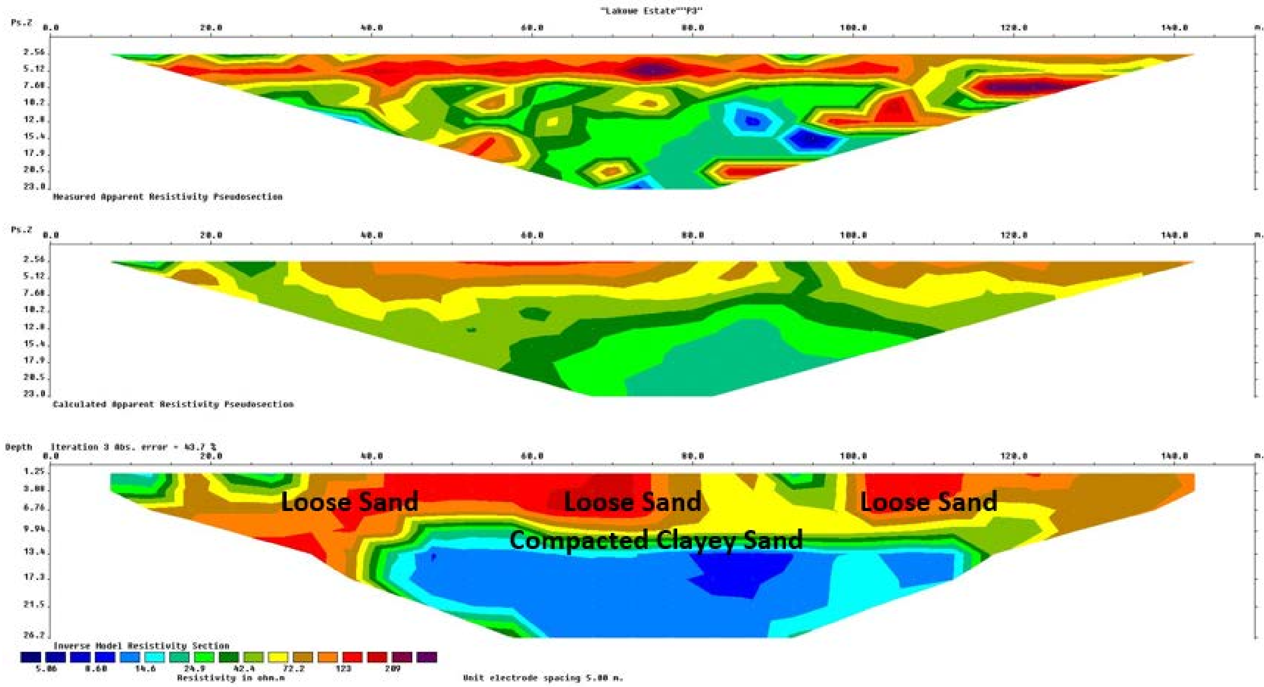


Figure 6: Inverse resistivity model of traverse P3

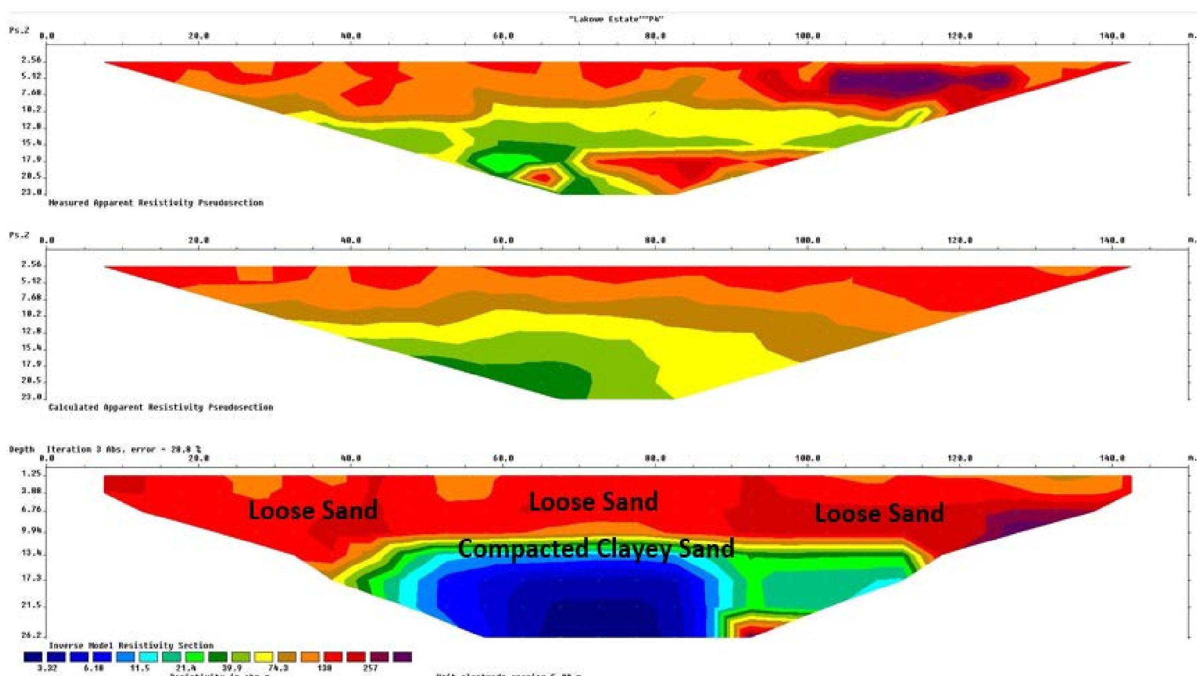
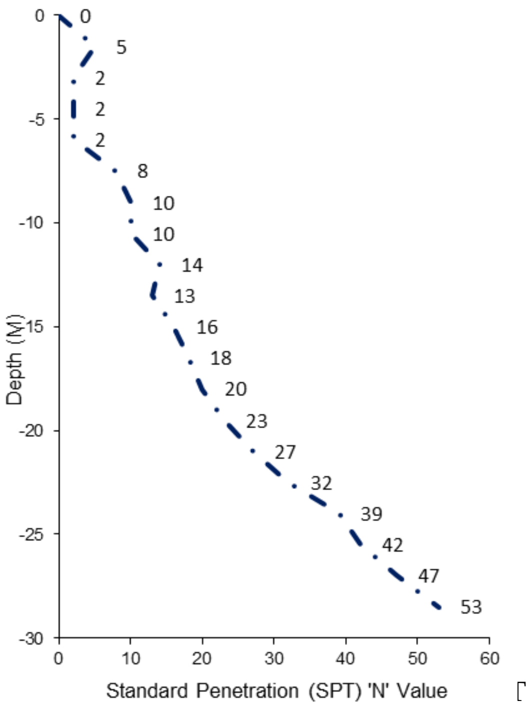
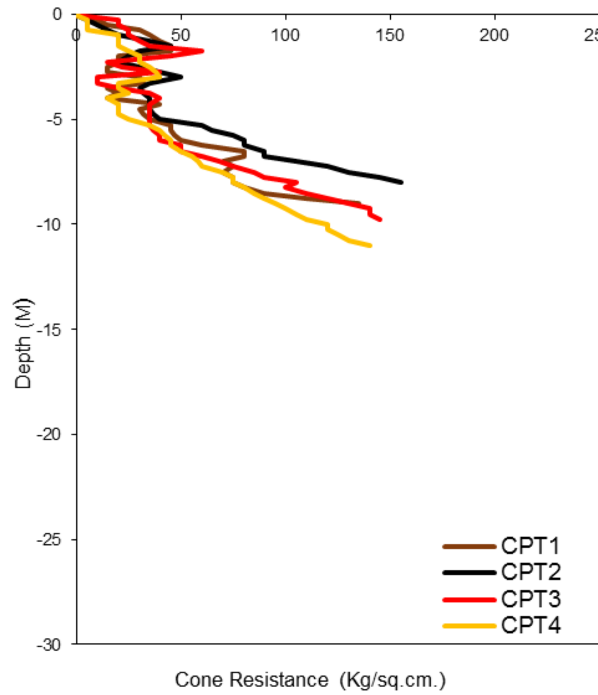


Figure 7: Inverse resistivity model of traverse P4





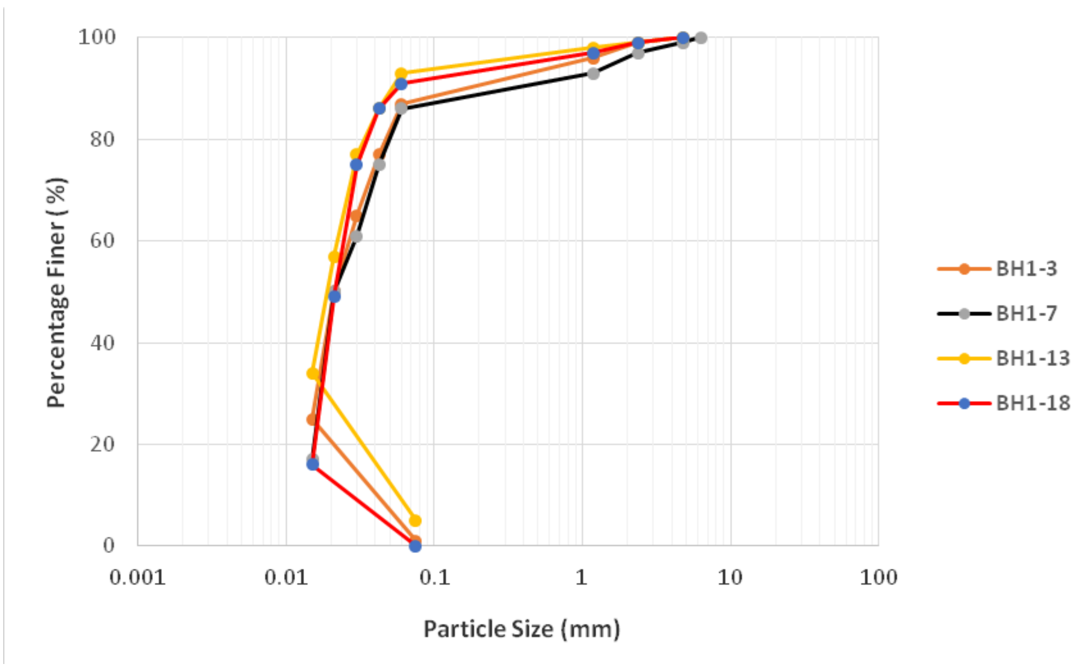


Figure 9: Particle Size Distribution Curves for Soil Samples 3 - 18

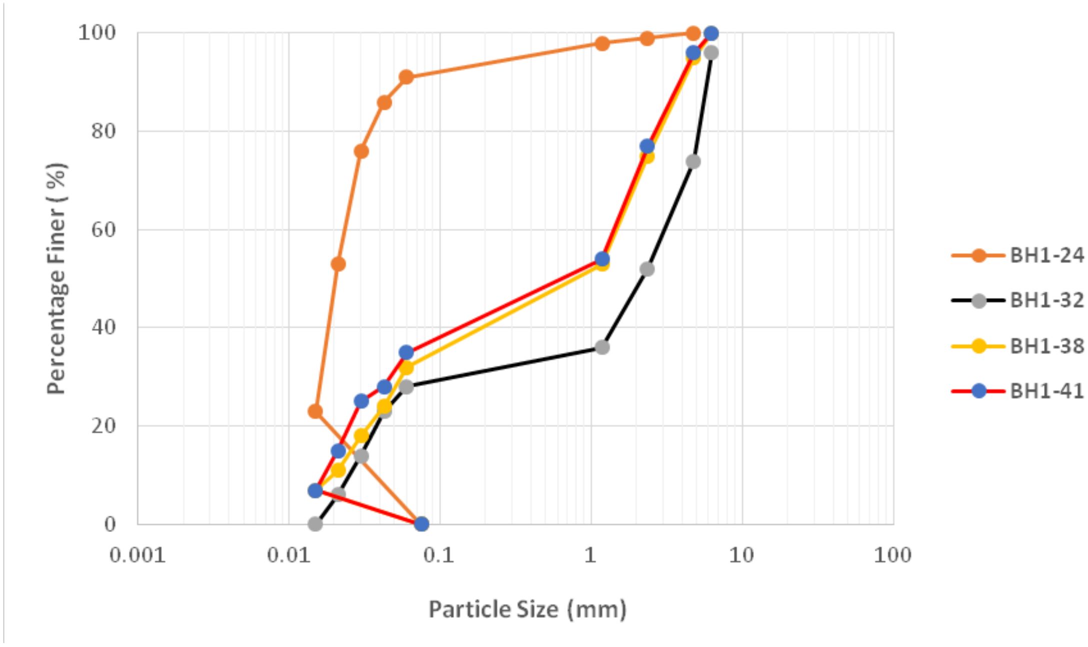


Figure 10: Particle Size Distribution Curves for Soil Samples 24 – 41

Table 1: Soil Borehole Log showing the Stratification/ Description of the Subsoil Encountered

Zone	Legend	Depth (m)	Soil Description	*Average SPT (N) value	Ranges of CPT Value q_c(Kgf/sq.cm)
1		0 -2.25	Loose, brown silty fine-medium grained sand with occassional fine gravels	5	5 – 60
2		2.25 -6.75	Soft, dark grey silty clay	2	5 – 45
3		6.75 -30.0	Medium dense to dense, grey sand (fmc) with fine grained gravels in places	25	60 – 145

Water Table – 1.50 m.

SPT (N) is the blow count value for 300 mm penetration after initial seating drive of 150 mm.

Table 2: Approximate Relationship between Relative Density, SPT, CPT and Ø° for In-Situ Soil (Meyerhof, 1965)

Zone	Legend	Depth (m)	Soil State	Average SPT (N) value	Average CPT Value q_c(MPa)	Relative Density	Ø°
1		0-2.25	Loose	5	3.24	0.2	30
2		2.25 -6.75	Loose	2	2.45	< 0.2	30
3		6.75 -30.0	Medium Dense	25	10.10	0.5	35

CONCLUSION

Electrical resistivity imaging and geotechnical investigations were carried out to investigate the subsoil conditions of Gioni estate Lakowe, Lekki-Epe , Lagos in southwestern Nigeria with a view to understand the near surface geoengineering characteristics for foundations studies and other building construction projects within this area. Three main lithologies including loose sand, clayey sand and clay/peat units were delineated based on their geoelectrical and geotechnical properties. The soil stratigraphy encountered on the test site revealed a near surface of loose silty sand to a depth of 2.25 m underlain by soft silty clay to a depth of 6.75 m below the existing ground level. Underlying this stratum of soft silty clay to depth of boring of 30 m occur medium dense sand becoming dense sand at depth. The subsoil conditions revealed within the investigated area is predominantly cohesionless soil materials, except for the 4.5 m thick of plastic silty clay layer encountered. In view of the medium compressibility of the near surface soil material, the use of raft foundation can be used to support some magnitude of load from the proposed building. However, loading the near surface soil will result in consolidation settlement of the plastic clay layer and this should be taking into consideration during the design and construction stages. The choice of deep seated foundation such as pile foundation is considered a better alternative to shallow foundation for proposed buildings in the investigated area where higher loadings are anticipated to transmit the loads to a stable soil layer.

Table 3: Summary of Laboratory Test Results

Sample No.	Depth (m)	Natural Moisture Content (%)	Atterberg Limits			Grading Analysis (% Passing)						Sample Description	Remarks
			W_L	W_P	PI	3.35 mm	2.0 mm	425 µm	300 µm	600 µm	75 µm		
BH1/3	1.50	11.5				100	99	87	77	65	1	Sand	Non-plastic
BH1/5	3.75	66.0	84	30	54							Organic Clay	Plastic
BH1/7	5.25	23.0				100	99	93	86	75	17	Silty sand	Non-plastic
BH1/13	9.75	15.0				100	99	93	86	77	5	Sand (fmc)	Non-plastic
BH1/18	13.50	15.8				100	99	91	86	75	0	Sand (fmc)	Non-plastic
BH1/24	18.00	13.5				100	99	91	86	76	0	Sand (fmc)	Non-plastic
BH1/32	24.00	14.0				96	74	36	28	23	0	Sand (fmc)	Non-plastic
BH1/38	28.50	14.3				95	75	32	24	18	0	Sand (fmc)	Non-plastic
BH1/39	29.50	14.0				95	73	32	24	19	0	Sand (fmc)	Non-plastic
BH1/41	30.00	15.6				96	77	35	28	25	0	Sand (fmc)	Non-plastic

W_L: Liquid Limit, W_P: Plastic Limit, P.I: Plasticity Index

Table 4: Summary of Particle Size Distribution and Soil Grained Classification

Sample No.	Depth (m)	Grading Analysis (% Passing)						Uniformity Coefficient (C_u)	Coefficient of Curvature (Cc)	USCS Classification
		3.35 mm	2.0 mm	425 μm	300 μm	600 μm	75 μm			
BH1/3	1.50	100	99	87	77	65	1	2.50	1.16	SP
BH1/7	5.25	100	99	93	86	75	17			SM
BH1/13	9.75	100	99	93	86	77	5	2.75	1.11	SP
BH1/18	13.50	100	99	91	86	75	0	1.71	1.07	SP
BH1/24	18.00	100	99	91	86	76	0	2.30	1.41	SP
BH1/32	24.00	96	74	36	28	23	0	8.42	1.00	SW
BH1/38	28.50	95	75	32	24	18	0	7.50	1.00	SW
BH1/41	30.00	96	77	35	28	25	0	7.50	1.05	SW

USCS – Unified Soil Classification System

SP: Poorly Graded Sand, SW: Well Graded Sand, SM: Silty Sand

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