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SUBSOIL CHARACTERIZATION USING GEOELECTRICAL AND GEOTECHNICAL INVESTIGATIONS: IMPLICATIONS FOR FOUNDATION STUDIES

Oyeyemi, K. D, Aizebeokhai, A. P, Adagunodo, T. A.
Department of Physics, Covenant University, Ota, Nigeria

Olofinnade, O. M
Civil Engineering Department, Covenant University, Ota, Nigeria

Sanuade, O. A
Department of Geophysics, Federal University Oye-Ekiti, Nigeria

Olaojo, A. A
Department of Geophysics, Federal University Oye-Ekiti, Nigeria

ABSTRACT

Electrical resistivity tomography (ERT) has been combined with geotechnical techniques such as cone penetrating tests, standard penetrating test and laboratory tests for detailed characterization of near-surface strata. This approach can be very helpful in conducting preliminary investigations towards a robust foundation design at a building construction site. Two ERT lines were conducted for 2D geoelectrical resistivity measurements using Wenner array configuration in combination with four cone penetrating data. Through the inversion of ERT data, two geoelectrical layers were interpreted to be loose silty sand and compacted clayey sand lithological units with the resistivity values ranging 50 – 280 Ωm and 10 – 74 Ωm respectively. A water-saturated portion with resistivity values ≤ 3 Ωm due to lagoon-water incursion was equally observed at the base of the second clayey sand layer in ERT line T2. The average cone penetrometer (CPT) value of about 110 kg/cm^2 (11 MPa) with an average SPT 'N' value of 25 was measured between 6.75 – 30.0 m, indicating that the geomaterials within this depths range are of good geotechnical properties. Laboratory tests conducted on the representative soil samples at 3.75 m depth gives a moisture content (MC) of 66%. This is attributed to the clay contents within the soil samples. The Liquid Limit (W_L), Plastic Limit (W_P) and Plasticity Index (PI) tests of the soil samples gives 84%, 30% and 54% respectively. The results of the proposed approach, encompassing both geophysical and geotechnical methods has helped to steer the choice of the foundation for the investigated building towards a pile-type foundation rather than a *shallow one. The pile foundation will cause the higher loadings to transmit the loads to a stable soil layer within the subsurface.*

Key words: Geomaterials, Electrical Resistivity Tomography, Geotechnical Investigation, Foundation Studies.

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1. INTRODUCTION

A thorough near-surface investigation and characterization prior to building construction is an essential component of foundation design 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. Heterogeneity and variations in the subsurface environments necessitated detailed geological and geoengineering investigations of a construction site in order to design effective earthworks and structural foundations. Applications of several non-invasive geophysical techniques which provide spatial and temporal information on the subsurface structures as well as fluid presence and its motion are increasingly been used in near-surface characterization at engineering and geotechnical sites over the last few decades as borehole drillings have become expensive. These techniques include seismic reflection and refraction [1–3], seismic surface wave [4], ground penetrating radar [5], very low frequency electromagnetic (VLF-EM) and EM-31 [6–7], and geoelectrical resistivity [8–14] techniques among others. Geophysical methods are capable of precisely mapping depth to bedrock, bedrock topography and architecture, depth to the groundwater table as well as the lateral and vertical inhomogeneity of sub-soil properties at geotechnical sites. The resolution of the geophysical data can provide additional insight into the subsurface geology and the causes of foundation failures. These data can also serve as a guide to optimize siting of borehole locations for coring and soil samples collection, which are essential in designing the restoration intervention.

Electrical resistivity tomography (ERT) is one of the most popular geophysical tools for near-surface characterization. This is perhaps based on its speed of data acquisition, cost effectiveness and proxy to the spatial and temporal variability of many other subsurface physico-chemical properties such as soil types, porosity, moisture content, clay content and mineralogy, soil water content, organic matter, and bulk density. Clay content for instance can affect the soil strength, porosity and ultimately the conductivity (or resistivity) of the soil matrix in various degrees. The ion exchange property of clay lithology forms a mobile cloud of ions around each clay particle, which then expedite the 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 [15]. Generally, electrical resistivity tomography technique has proven to be non-destructive, minimally invasive and has been applied to various subsurface characterization problems involving groundwater exploration, engineering site investigations, landfill and solute transport delineation, determination of compaction and soil horizon thickness, archaeological prospecting, and assessment of both soil hydrological properties and foundation instability [16–20].

Alternatively, the invasive geotechnical techniques such as cone penetrating test (CPT) and standard penetration test (SPT) can also provide direct and precise information regarding the soils' resistance to penetration which is dependent on the soil strength in terms of the N-values.

These values are often referred to as the number of blows per 30 cm of penetration into the soil, and based on the procedure of IS 6403 code [21], they can be used to estimate the bearing capacity of soils. The geotechnical dataset from CPT and SPT are principally essential for subsurface soil characterization and foundation studies when they are integrated with the borehole data and laboratory tests of soil properties (e.g. grain size distribution, degree of saturation and permeability) [7]. The aim of this research work is:

- To characterize the subsoil lithologies at a building construction site using geoelectrical resistivity imaging;
- To conduct geotechnical analyses of subsurface geomaterials using in-situ
- Borehole measurements, laboratory, cone penetrating, and standard penetrating tests;
- To integrate together the evidences of both methods in order to propose a more
- Suitable foundation type in the study area.

2. METHODOLOGY

2.1. Site Description

The construction site of study is situated within the Unity Estate (Lat. 6°30′N and Long. 3°37′ E), Ajah Lagos-island, south-western Nigeria. This part of Lagos is an area of land around the inlet of the sea into the extensive Lagos harbour lagoon system, and is generally low lying with several points virtually at sea level making them prone to flooding. Two principal climatic seasons characterized the Lagos-island, a dry season from November to March and a wet (or raining) season which starts in April and ends in October with a short break in mid-August. Occasional rainfalls are often witnessed within the dry season due to the proximity of this area to the Atlantic Ocean. The mean annual precipitation is above 1800 mm and serves as a major source of groundwater recharge.

Lagos-island is situated within the eastern part of the Dahomey Basin, southwestern Nigeria (Fig. 1). This basin is a combination of inland, coastal and offshore basins that stretches along the continental margin of the Gulf of Guinea. Five geomorphological sub-units were recognized within the coastal landscape [22] and they are (i) abandoned beach ridge complex, (ii) coastal creeks and lagoons, (iii) swamp flats, (iv) forested river floodplain, and (v) active barrier beach complex. Stratigraphically, the Dahomey Basin has been categorized into Abeokuta Group, Ilaro Formation, Coastal Plain Sands and Recent Alluvium sediments [23]. Cretaceous sequence of Abeokuta Group consists of Ise, Afowo and Araromi Formations [24]. Ise Formation is the oldest and consists of conglomeratic sandstones at base, which in turn is overlain by coarse-medium sands with interbedded kaolinite. The next is Afowo Formation, predominantly coarse-medium sandstones with variable but thick interbedded shales, siltstones and claystone.

Overlying the Afowo Formation is the Araromi Formation, which has been reported to be the youngest Cretaceous sediment in the entire eastern Dahomey basin [24]. Araromi Formation is composed of fine to medium grained sandstone overlain by shales, siltstone with interbedded limestone, marl and lignite lithological units. The next is Ewekoro which is an extensive limestone rock type. Akinbo Formation underlies the Ewekoro Formation and is made up of shale and clayey lithologic sequence [25]. Overlying the Akinbo Formation is Oshosun Formation which consists of greenish – grey or beige clay and shale with interbeds of sandstones.

The Ilaro Formation overlies conformably the Oshosun Formation and consists of massive, yellowish poorly, consolidated, cross-bedded sandstones. The Quaternary sequence within the eastern Dahomey basin are the Benin Formation (Miocene-Recent), Lagoon/Coastal Plain Sand deposits and the recent littoral alluvium [26–27]; the lithoral alluvium consists of poorly sorted sands with lenses of clays. The sands from Oligocene to Recent are in parts cross bedded and show transitional to continental characteristics. The local geology as revealed by the lithostratigraphic information from boreholes in and around Lekki-Ikoyi area is a typical stratigraphic cross-section of unconsolidated dry and wet sands, and organic clay deposit. The deposits are sometimes interbedded in places with sandy-clay or clayey-sand and mud with occasional varying proportion of vegetable remains and peat. The environment of deposition of these sediments has been suggested to be near-shore littoral and lagoonal [27].

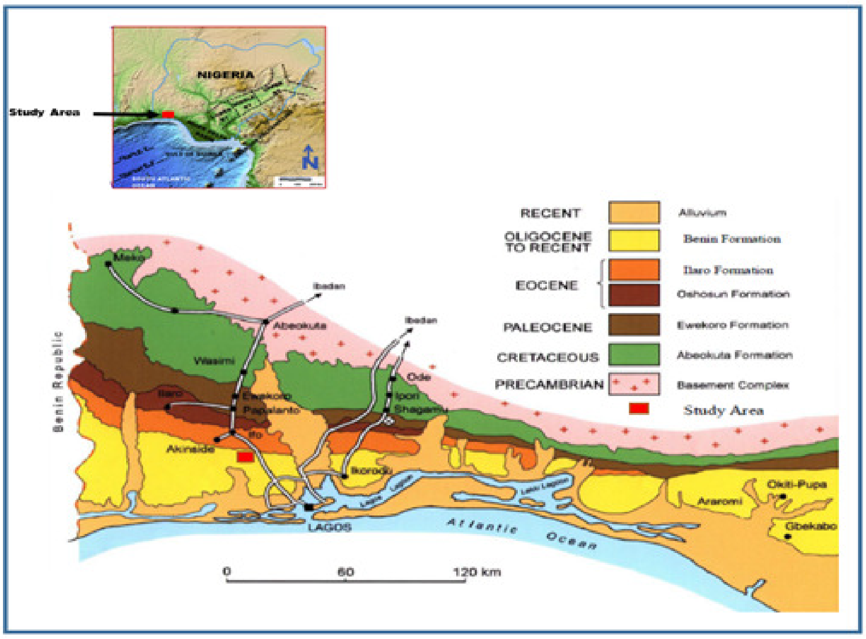


Figure 1 Geological map of the Nigerian part of the Dahomey embayment with an inset map of Nigeria showing the location of study (modified after [28]).

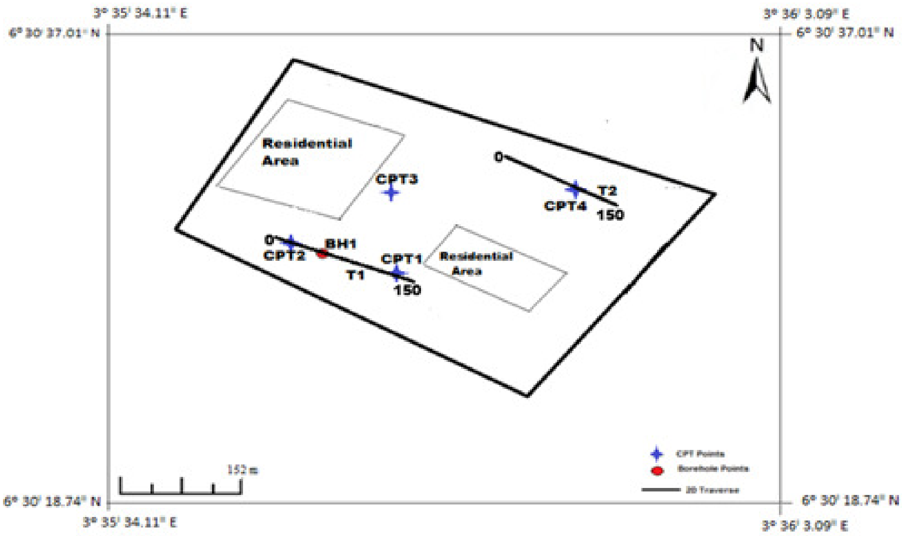


Figure 2 The basemap for data acquisitions.

2.2. Electrical Resistivity Tomography (ERT)

The location of geophysical and geotechnical surveys is presented in Fig. 2. Two-dimensional ERT investigations were conducted using an ABEM Terameter (SAS 1000/4000 series) along the two main survey traverses (T1 and T2 in Fig. 2). The ERT lines, NW-SE directed have a length of 150 m each and were acquired using a Wenner array with minimum and maximum electrode spacing of 5.0 m and 45.0 m respectively, resulting in 9 depth levels. A total number of 288 data points (apparent resistivity) were acquired using a cycle of four stacks for each quadrupole and a maximum threshold of 0.2% for the observed root mean square error. The observed apparent resistivity data were processed and inverted using RES2DINV code, employing a least squares inversion modelling technique with regularization technique [29].

2.3. Cone Penetrometer, SPT and Boring

The estimation of the physical and mechanical properties of the subsoil was conducted using the code of practice for site investigation (BS 5930) [30]. Four Nos. Dutch cone penetrometer test (CPT) denoted as CPT1, CPT2, CPT3 and CPT4 were acquired using a 2500 kg capacity penetrometer machine. High resistance to further subsoil penetration limited the CPT tests to terminate at depths ranging from 8.0 m to about 11.0 m. Standard penetration tests (SPT) were equally carried out at every 1.50 m intervals to determine the relative densities in both cohesive and non-cohesive strata. The tests were performed by driven a split spoon sampler of 5 cm diameter through the cohesionless strata and obtained 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. One No. shell and auger borehole designated as BH1 was also drilled up to the depth of 30 meters using a Dando percussion boring rig. In the course of boring, 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.

2.4. Laboratory Testing

Moisture contents and other testing such as 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) [31]. 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. The samples having an approximate weight of 500 g was washed using No. 200 sieve (0.075 mm) to separate the silt, clay and sand based on grain sizes. 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 used was BS 5930 [30].

3. RESULTS

The subsurface characterization using geoelectrical resistivity depends on several factors such as soil water content, grain size distribution, void ratio, porosity, permeability and density. For instance, low soil water content in soil with high air filled void will result in high geoelectrical resistivity. The soil porosity will equally decrease in a lithology with finer grain size, thereby increasing the resistivity values. Also, air filled void soil type will have higher geoelectrical resistivity values contrary to a water filled void soil type. In fine grained subsoil materials such as clay, where soil water content is higher, the observed geoelectrical resistivity is usually low.

The inverted resistivity models of the T1 and T2 ERT lines revealed the presence of two distinct geoelectrical layers across both traverses (Figs. 3 and 4); topsoil which is largely composed of loose silty sand unit with apparent resistivity values ranging from 50 to 280 Ωm, this is underlain by the second layer of compacted wet sand units with clay intercalations (10 – 74 Ωm). The extremely low geoelectrical resistivity values ($\leq 3 \Omega m$) observed at the base of the traverse T2 is suspected to be the water incursions into the clayey sand unit from lagoon due to the location of the study area within the Lagos-island. The top loose silty sand layer with a consistent thickness of about 14.2 meters across both traverses, appears to be the materials used in sand-filling the area prior to building construction of the estate. This layer overlies conformably a clayey sand layer at the base. The results of the ERT and the evaluated geoelectrical layers are in line with that of other researchers [32–33].

The subsoil conditions as shown in 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 are 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 (ϕ^o) according to Meyerhof [34]. It clearly indicates that the near surface soil materials are of loose relative density, soft consistency and high compressibility potential. It also shows that very limited magnitude of structural loading can be supported by the near surface in-situ soil materials. The results of the SPT 'N' value and CPT confirm that the near surface geomaterials within 0-6 metres have poor geotechnical properties with low shear strength and high compressibility potential. Average Cone penetrometer (CPT) value gives about 30 kg/cm^2 (3 MPa) with an average SPT 'N' value of 5. This connotes that the geomaterials closer to the surface above 6.75 m are poor in terms of geotechnical properties and may not be able to support building foundations efficiently. However, the soil materials underlying this weak near-surface 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 (11 MPa) with an average SPT 'N' value of 25 from 6.75 metres to about 30.0 metres. This is an indication that the soil material within these depths (6.75 m) are of good geotechnical properties.

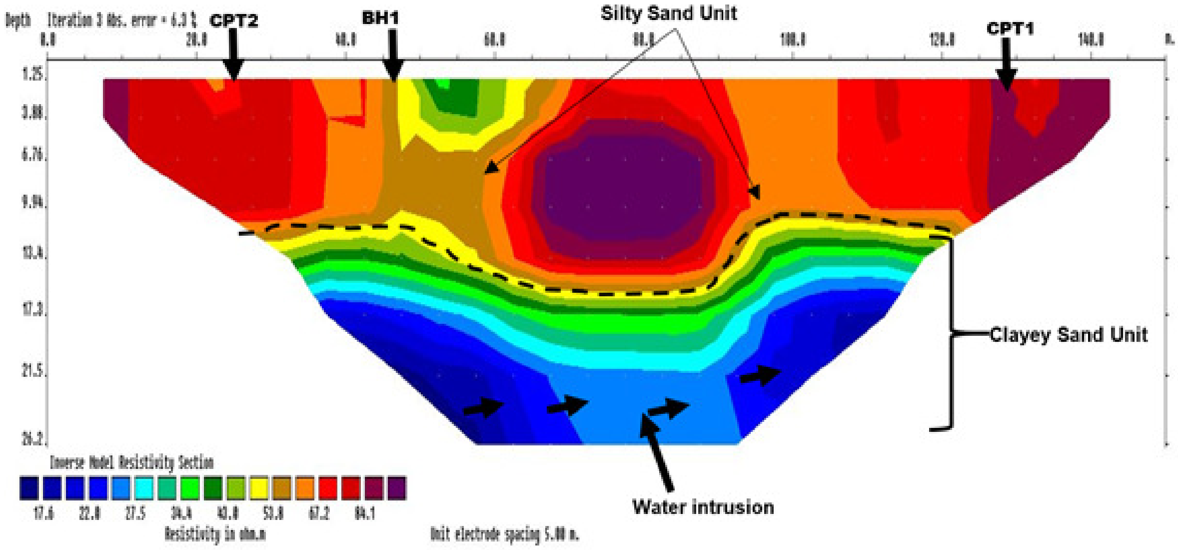


Figure 3 Inverse resistivity model of the ERT line T1

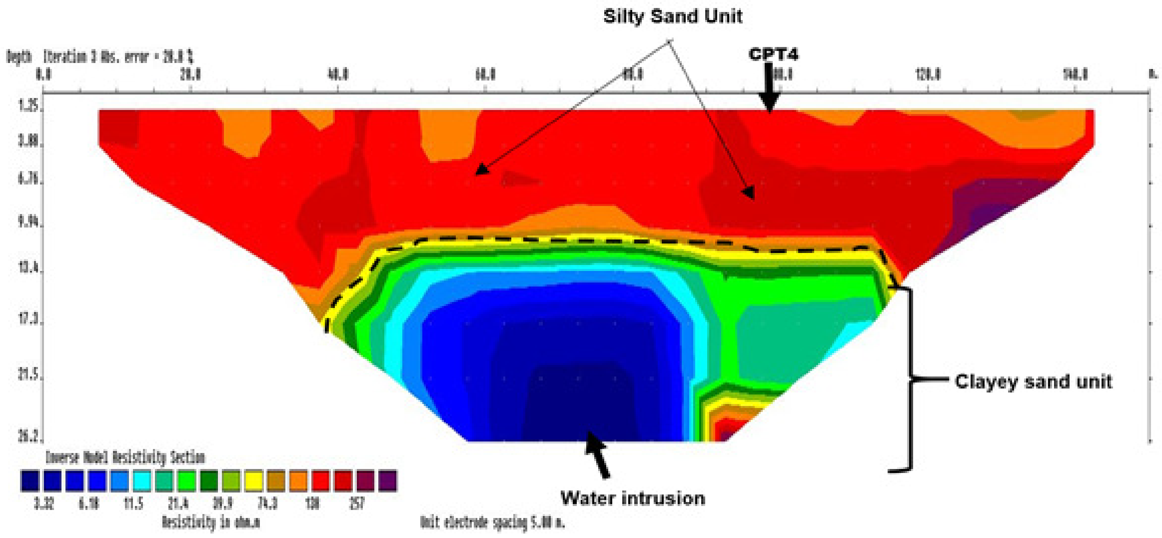


Figure 4 Inverse resistivity model of the ERT line T2

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 clay 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.

3. DISCUSSION

Integrating both geoelectrical and geotechnical results for subsoil characterization 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 suspected to be non-expansive type, they are not prone to anomalous dilatation (volume changes) through swelling and shrinking; therefore, they may not compromise the integrity of building foundations in the area. Furthermore, the boring log and penetrometer plots show that the near surface soil consists approximately 2 m thick of loose silty sand. 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. 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.

Thus the above findings have further demonstrated that conducting geophysical investigations before boring and other geotechnical methods can serve as good prospects in subsoil characterization for foundation design. Combining geophysical methods such as ERT with geotechnical techniques will assist and improve the confidence levels of engineers in making decisions regarding the suitable foundation type for building construction. Also, acquisitions of geophysical data like electrical resistivity tomography will help guiding the engineers in designing restoration interventions where necessary by optimizing borehole locations for coring and collection of soil samples purposes. ERT is a robust, cost effective and non-destructive geophysical technique that can be conducted using several array such as Wenner, Wenner-Schlumberger and Dipole-Dipole array configurations for better vertical and lateral subsurface resolutions without compromising their depth of investigation (DOI). This technique produces two dimensional subsurface imaging to predict and characterize the subsoil materials, which will enable the engineers to obtain more data economically. Electrical resistivity tomography is therefore recommended as a preliminary geophysical technique in geotechnical engineering because it is non-invasive and eliminates any form of site near – surface damageability, thereby contributing significantly to the sustainable green environment in construction industry.

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

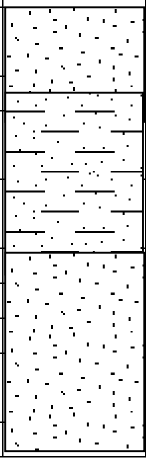
Zone	**Legend**	**Depth (m)**	**Soil State**	**Average SPT (N) value**	**Average CPT Value q_c(MPa)**	**Relative Density**	**Ø°**
1		0-2.25	Loose	5	3.24	0.2	30
2		2.25 - 6.75	Loose	2	2.45	< 0.2	30
3		6.75 - 30.0	Medium Dense	25	10.10	0.5	35

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

4. CONCLUSION

Investigation with a view to understand the near surface geoengineering characteristics for foundations studies and other building construction projects was done using integrated electrical resistivity tomography and geotechnical studies. Two main lithologies including loose silty sand and clayey sand units were delineated based on their geoelectrical and geotechnical properties. Relatively low cone penetrating test (CPT) and standard penetrating tests (SPT) values of the strata above 6.75 m render them not suitable for foundation design. The soil stratigraphy encountered on the test site using ASTM [35] 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.

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