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Original Research Article

2D Geophysics and in-situ Geotechnical Exploration of an Engineering-Challenged Site in Southwestern Nigeria

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ABSTRACT

Failure of structures due to inadequate foundation investigation is imminent at Westwood Development Estate, Sangotedo area of Lagos. This calls for an integrated method for site investigation of the underlying geological medium in the area. In this study, geophysical and geotechnical approaches were to define the number of subsurface soil layers, their thicknesses and established the depth to competent layers. Voltages of electrical field induced by the distant grounded current electrodes were measured and interpreted based on the apparent electrical resistivity (ρ_{app}) values as the function of depth. The geotechnical method was done by pushing an instrumented cone and a sample tube into the ground. Cone penetration resistance (q_c) and tube's number of blows at 150 mm to various depths were recorded. From both methods and borehole logs, topsoil has ρ_{app} values range of 283-1128 Ωm with q_c and respective allowable bearing capacity (ABC) ranges of 2 - 40 kg/cm^2 and 529 – 10584 kN/m^2. The second layer (loose fine to coarse grained sand) had ρ_{app} range of 226 – 2544 Ωm and q_c (2 - 40 kg/cm^2) with ABC range of 10584 – 31752 kN/m^2 respectively. The third and fourth layers composed mainly of medium dense fine to coarse grained sand. The top layer to a depth of 1.4 m may be inimical to foundation of any structure, and require excavation. Moderate structures such as bungalows and a storey building can be accommodated at 3.0 m depth. However, pile foundations are recommended at greater depth for medium to high rise structures.

1. INTRODUCTION

Several researchers have employed in-situ measurement to acquire information about the nature of subsurface conditions in their environment. Adepelumi *et al.* (2009) employed cone penetrometer and finite element methods to characterize sand-fill thicknesses in coastal area. It was revealed that structural trend of the depressions in the reclaimed part of the area have been influenced by the oceanic fracture pattern. Oyedele *et al.* (2011) integrated both geophysical and geotechnical methods to characterize the foundation materials in a similar environment. The vertical electrical sounding results revealed four to five subsurface layers with low penetration resistance values to a depth of 16 m in the coastal plain sands and recent littoral alluvium of the Dahomey basin.

Certainly, satisfactory geotechnical information for site investigation in areas underlain by stratified rocks is difficult to acquire (Bell *et al.,* 1990). This is because soil characteristics tend to be altered when recovered, even with core cutters for laboratory foundation geotechnical assessment (Lunne *et al.,* 1997). Therefore, test results on undisturbed samples cannot be scaled in any way to directly predict the behaviour of a full scale construction (Adebisi and Fatoba, 2013). Adebisi and Fatoba (2013) to an extent, revealed the composite nature and variability of the underlying lithology of some part in Lagos State, Nigeria, for the foundation design. Adebisi *et al.* (2016) in an in-depth investigation assessed the foundation soils at Ibeju Lekki, creek area of Lagos. The study only elucidated earth pressures for construction projects to be founded over subsoils in the area. However, it recommended the California bearing ratio and compacted density for sub base thickness with layers compacted at optimum moisture content to take cognisance of probable groundwater level fluctuation in the area. Adebisi and Oluwafemi (2017) again instituted a study on geotechnical properties of soils which underlain the certain part of the coastal area of Southwestern Nigeria. The study accounted for more detailed characteristics for foundations design and analysis. In spite of high degree of water and (low) organic content, the soil was observed to have low compressibility and sufficiently high strength characteristics at considerable foundation depths.

However, previous works are yet to maximize the in-situ methods to critically address the limited engineering interpretation of explaining complex shallow subsurface geology of the coastal area. Hence, this study employed a 2D electrical resistivity survey to effectively represent the subsurface geometry, and apply the lithological information to foundation design through integrated geotechnical data approach. These are expected to bridge gap in knowledge regarding the determination of subsoils competency in such an engineering-challenged environment.

2. MATERIALS AND METHODS

2.1. Description of Study Area

The study area is at Westwood Estate Sangotedo, in Ajah part of Lagos State. It is enclosed within longitudes 03° 22'05.45''E - 03° 22'05.84''E and latitudes 06° 28'32.18''N and 06° 28'37.31''N (Figure 1). It is a low-lying land with sparse vegetation and sand filled to varying thicknesses. The entire area is dominated by the Lagos lagoon which numerous streams and rivers drain into. This area is underlain by stratified rocks of the Dahomey Basin above actuate coastal basin, the onshore parts of which is dominated by the Recent-Quaternary Coastal Plains of Sands. A profile of sand, sandy clay and lignite, with vegetated freshwater deposits extends to a depth of 1.5 m and groundwater level 0.25 m (Adebisi *et al.*, 2016). In general, spongy brownish grey organic to fine-medium-grained silty sands exist from ground level to a depth of 0.5 m.

The 2-D constant separation traversing (CST) and the vertical electrical sounding (VES) resistivity methods of electrical resistivity imaging (ERI) were employed using PASI resistivity meter and its accessories for the electrical resistivity tomography (ERT). In-situ geotechnical testing to measure the resistance of the soil strata to the penetration made use of Dutch cone penetrometer test (CPT) and standard penetration test (SPT) borehole methods whose tests procedures followed the British Standard Institution (1999). Various Bearing Capacity values were determined in accordance the British Standard Institution (1990). Figure 2 shows the geophysical measurement layout, and geotechnical test points in the study area.

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Figure 1: True colour composite, satellite imagery of Ajah showing the study area

In the constant separation traversing (CST), Werner's electrodes configuration array was used. This followed a survey line with keeping the electrode separations constant. The VES was performed based on the measurement of voltage of electrical field induced by distant grounded current electrodes. The current electrodes were connected to a current source, while the potential electrodes were used for the voltage measurements. The VES curves were plotted, and their quantitative interpretation was used to obtain the geoelectrical parameters and geoelectric section. The interpretation of the measurements was performed based on the apparent resistivity (ρ_a) values. The ERI was used to determine the subsurface electrical resistivity distribution via electrical measurement on the ground surface. The ERT data were processed into profiles, which consist of a modelled cross-sectional (2-D) plot of resistivity (*Ωm*) versus depth.

For the CPT, an instrumented tipped-cone with an apex angle of 60° and cross-section area of 1000 mm^2 was pushed into the ground at a controlled rate on a 2.5 tons penetrometer. This was done with a number of rods of 2.5 m each in length. The resistance of the cone to foundation soil (cone penetration resistance - q_c) was then recorded with depth. The SPT made use of a thick-walled sample tube driven into the ground at the bottom of a borehole by blows from a slide hammer falling through a distance on a tripod percussion rig. The number of blows required to advance the sample tube through a 150 mm penetration interval is the standard penetration resistance. This was denoted as N_{spt}-value, and recorded against the tube penetration depth. The q_c from CPT and the N_{spt}-values from SPT were used with some engineering geotechnical formulae in the determination of bearing capacities of the soils using 3 as a factor of safety (FoS).

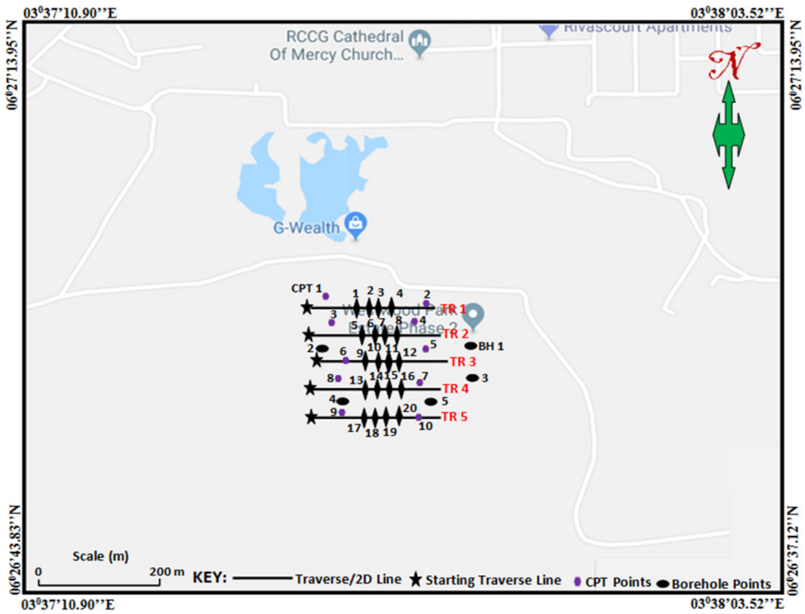

Figure 2: Map of Ajah showing the geophysical measurement, and geotechnical testing locations in the study area

3. RESULTS AND DISCUSSION

On the basis of materials observed during SPT, penetration resistance (q_c), and N_{spt}-values, it is possible to describe the various layers that make up the foundation materials in the study area. The logs of SPT geotechnical boreholes which show representative of foundation materials in the area are illustrated in Figure 2 with depth. From the ground surface to a depth of 1.50 m, the profile comprises of very loose to loosely grey brownish fine silty sand. These are filling materials with fibrous roots in some places with N_{spt}-values ranging from 2 to 4, while the cone resistance reading from the penetrometer ranges from 0 to 30 kg/cm^2. However, between the depth of 0.75 and 6.0 m, there are loose greyish brown silty fine sands with intercalations of peaty sands in some occasions with N_{spt}-value from the borehole ranging from 3 to 10 while the cone resistance reading from the penetrometer ranges from 15 to 118 kg/cm^2. Underneath the depth of 5.25 to 13.5 m, we have Loose to medium dense light brownish grey fine to coarse sand with silty sands in some places while tiny gravels in some place with N_{spt}-values range of 9 and 16. The penetrometer has reached its maximum before the anchor pull-out. Below the depth of 13.5 to 24.0 m is made of a layer of medium dense light brown fine to coarse sand with N_{spt}-value ranging from 15 to 29. Finally, below the depth of 22.5 to the termination of the bore hole at -30.00 mts is made of dense brown medium to coarse sand with occasional fine gravel with N_{spt}-values ranging from 30 to 45.

3.1. Sounding Curves and Geoelectrical Parameters

Three (3) major groups of VES curves were obtained from the electrical resistivity survey. These include KH, Q and K types shown in Figure 3 and are characteristic of three (3) to four (4) geo-electric layers. The K type curve is the most common of all the curves accounting for about 50 % of the total curves that were interpreted. Q type curve accounted for 25 %, while the KH accounted for the remaining 25 % of the entire VES curves interpreted in the study area.

In general, three-layer curve types (about 75 %) dominated the sounding, while that of the four-layer types accounted for the remaining 25 %. The quantitative geoelectrical parameters for true resistivities and the corresponding layer thicknesses obtained are summarized in Tables 1 and 2. The results of this interpretation gave further clue to delineating the soil stratigraphy for foundation potential of the subsoils in the area.

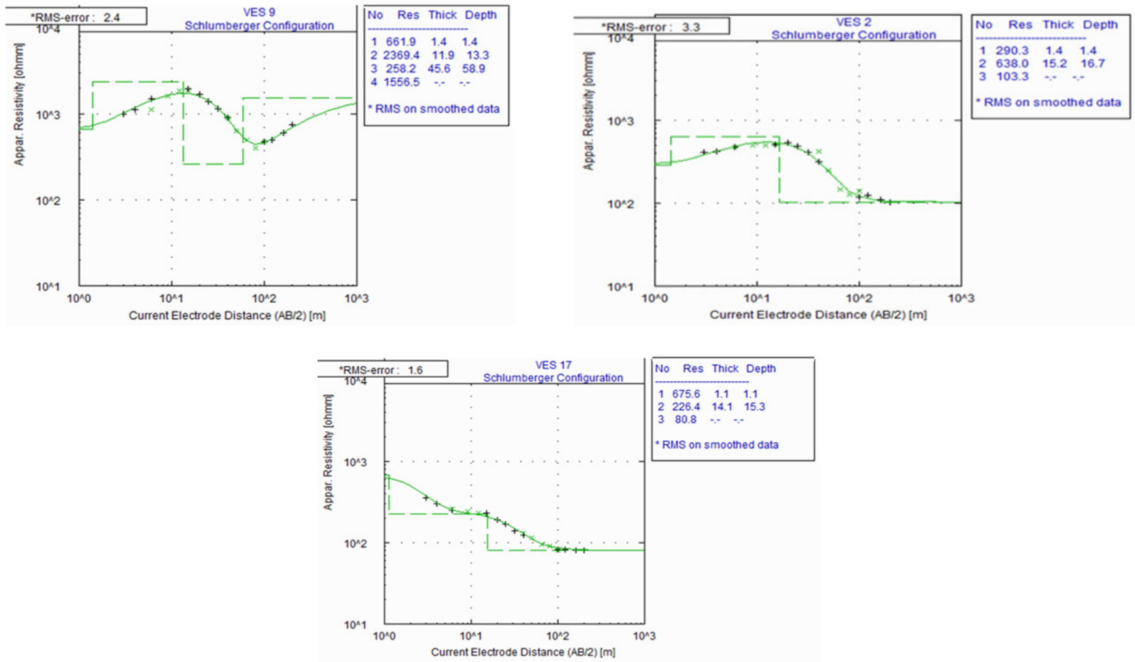

Figure 3: Selected electrical sounding curves from the geophysical measurement in the study area

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Table 1: Interpretation of vertical electrical sounding results (for VES 1 - 10)

VES	Layer	Resistivity(Ωm)	Thickness (m)	Depth (m)	Inferred lithology
1	1	283	1.3	1.3	Topsoil
	2	630	16.1	17.4	Loose fine to coarse grained Sand
	3	100	--	--	Medium Dense Sand
2	1	290	1.4	1.4	Topsoil
	2	638	15.2	16.7	Loose fine to coarse grained Sand
	3	103	--	--	Medium Dense Sand
3	1	487	1.1	1.1	Topsoil
	2	780	7.9	8.9	Loose fine to coarse grained Sand
	3	172	--	--	Medium Dense Sand
4	1	462	1.2	1.2	Topsoil
	2	822	7.0	8.1	Loose fine to coarse grained Sand
	3	179	--	--	Medium Dense Sand
5	1	452	1.2	1.2	Topsoil
	2	1132	5.8	7.0	Loose fine to coarse grained Sand
	3	100	--	--	Medium Dense Sand
6	1	601	1.2	1.2	Topsoil
	2	1042	7.0	8.2	Loose fine to coarse grained Sand
	3	165	--	--	Medium Dense Sand
7	1	739	1.2	1.2	Topsoil
	2	1088	8.7	9.9	Loose fine to coarse grained Sand
	3	175	--	--	Medium Dense Sand
8	1	775	1.2	1.2	Topsoil
	2	1072	8.7	9.9	Loose fine to coarse grained Sand
	3	179	--	--	Medium Dense Sand
9	1	662	1.4	1.4	Topsoil
	2	2369	11.9	13.3	Loose fine to coarse grained Sand
	3	258	45.6	58.9	Medium Dense Sand
	4	1557	--	--	Dense fine to Coarse grained Sand
10	1	739	1.1	1.1	Topsoil
	2	975	10.6	11.7	Loose fine to coarse grained Sand
	3	109	57.9	69.6	Medium Dense Sand
	4	1349	--	--	Dense fine to Coarse grained Sand

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Table 2: Interpretation of vertical electrical sounding curves (for VES 11 - 20)

VES	Layer	Resistivity(Ωm)	Thickness (m)	Depth (m)	Inferred lithology
11	1	607	1.4	1.4	Topsoil
	2	2544	9.4	10.9	Loose fine to coarse grained Sand
	3	259	55.4	66.2	Medium Dense Sand
	4	2531	--	--	Dense fine to Coarse grained Sand
12	1	730	1.1	1.1	Topsoil
	2	978	10.5	11.6	Loose fine to coarse grained Sand
	3	112	56.6	68.2	Medium Dense Sand
	4	1159	--	--	Dense fine to Coarse grained Sand
13	1	528	1.2	1.2	Topsoil
	2	940	8.4	9.6	Loose fine to coarse grained Sand
	3	63	--	--	Medium Dense Sand
14	1	1128	1.2	1.2	Topsoil
	2	701	11.4	12.6	Loose fine to coarse grained Sand
	3	140	--	--	Medium Dense Sand
15	1	1082	0.9	0.9	Topsoil
	2	1268	2.1	3.0	Loose fine to coarse grained Sand
	3	459	14.3	17.3	Medium Dense Sand
	4	3482	--	--	Dense fine to Coarse grained Sand
16	1	474	1.0	1.0	Topsoil
	2	972	10.5	11.5	Loose fine to coarse grained Sand
	3	67	--	--	Medium Dense Sand
17	1	676	1.1	1.1	Topsoil
	2	226	14.1	15.3	Loose fine to coarse grained Sand
	3	81	--	--	Medium Dense Sand
18	1	756	1.1	1.1	Topsoil
	2	300	12.0	13.1	Loose fine to coarse grained Sand
	3	123	--	--	Medium Dense Sand
19	1	702	1.0	1.0	Topsoil
	2	298	12.0	13.0	Loose fine to coarse grained Sand
	3	125	--	--	Medium Dense Sand
20	1	648	1.1	1.1	Topsoil
	2	283	13.3	14.5	Loose fine to coarse grained Sand
	3	127	--	--	Medium Dense Sand

3.2. CPT Curves and Foundation Design Geotechnical Parameters

Plots of cone resistance against depth for each of tested locations are shown in Figure 4. Few sharp peaks were observed in all the curves. Generally, there exists a gradual increase in cone resistance (2 – 40 kg/cm^2) within a depth range of 0 – 1.6 m and more rapid increase in cone resistance range of 40 – 120 kg/cm^2 within a depth range of 1.6 – 4.8 m across the study area. According to Garg (2007), within 0 – 1.6 m there exists very loose to fairly loose soil of low strength. Furthermore, they are very loose to loose soil to more competent medium dense sand layers at various CPT test points (Bowles, 1984; Kim *et al.*, 2006; Suzuki, 2015).

The estimation of the allowable bearing capacity from the ultimate bearing capacity (UBC) values was based on a factor of safety of 3.0 at various depth intervals as shown in Table 3 (Vesic, 1973; Bowles, 1988). Within the depth of 1.60 and 3.8 m, the soil has cone resistance values that range from 40 – 106 kg/cm^2. Tip resistance values range between 3920 and 10388 kN/m^2 with ABC range of 10584 - 28048 kN/m^2, while safe bearing capacity values range from 3528 to 9349 kN/m^2. At depth of 4.8 m, the soil has cone resistance of 120 kg/cm^2 with tip resistance value of 11760 kN/m, ABC of 31752 kN/m^2 and SBC of 10584 kN/m^2 were also recorded. These are characteristic of soils containing medium dense sand (Zumrawi and Elnour, 2016).

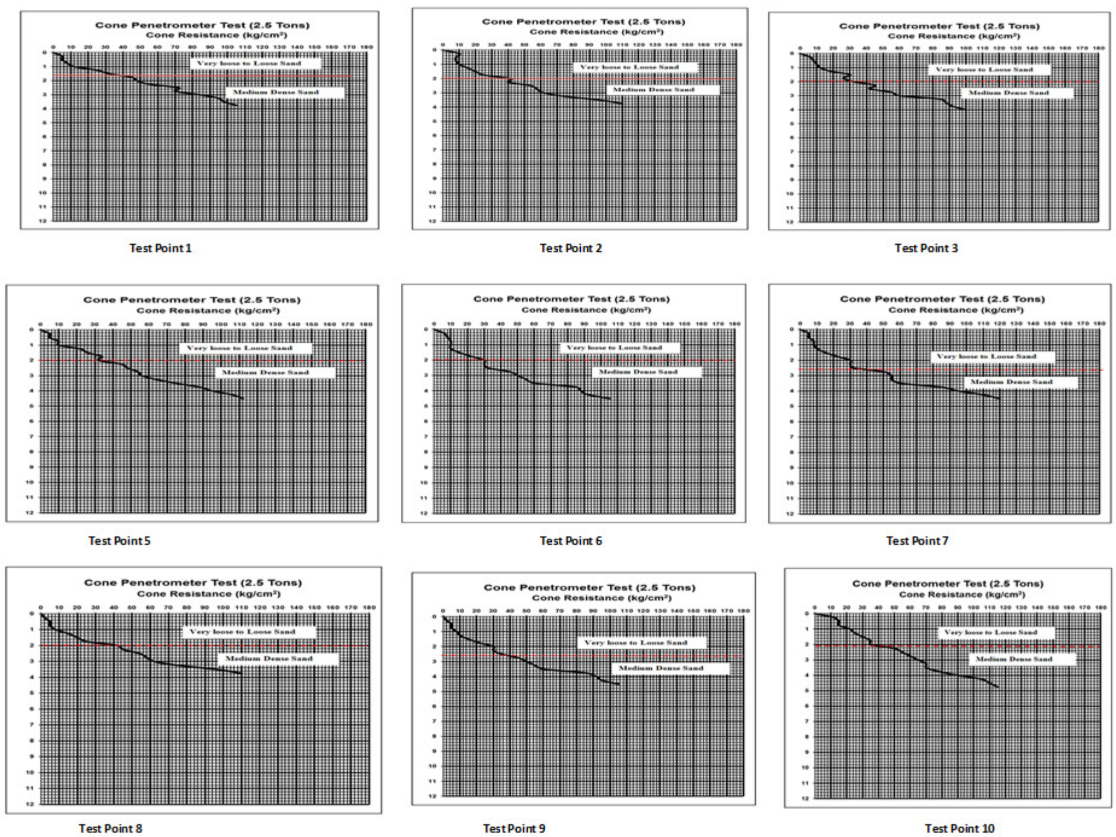

Figure 4: Selected CPT curves from the in-situ geotechnical measurement in the study area

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Table 3: Calculated ABC and UBC from the CPT values

Depth (m)	Cone resistance (qc) range (kg/cm^2)	Tip resistance (R_T) range (kg/cm^2)	Ultimate bearing capacity range (kN/m^2)	Allowable bearing capacity range (kN/m^2)
		CPT 1		
0.25 – 1.6	10 – 40	980 – 3920	2646 – 10584	882 – 3528
1.6 – 3.8	40 – 106	3920 – 10388	10584 – 28048	3528 – 9349
		CPT 2		
0.25 – 2.0	10 – 40	980 – 3920	2646 – 10584	882 – 3528
2.0 – 3.8	40 – 110	3920 – 10780	10584 – 29106	3528 – 7202
		CPT 3		
0.25 – 2.2	2 – 40	196 – 3920	529 – 10584	176 – 3528
2.2 – 4.0	40 – 100	3920 – 9800	10584 – 26460	3528 – 8820
		CPT 4		
0.25 – 2.6	4 – 40	392 – 3920	1058 – 10584	353 – 3528
2.6 – 4.8	40 – 120	3920 – 11760	10584 – 31752	3528 – 10584
		CPT 5		
0.25 – 2.2	5 – 40	490 - 3920	1323 – 10584	441 – 3528
2.2 – 4.5	40 – 112	3920 - 10976	10584 – 29635	3528 – 9878
		CPT 6		
0.25 – 2.6	5 – 40	490 – 3920	1323 – 10584	441 – 3528
2.6 – 4.5	40 – 105	3920 - 10290	10584 – 27783	3528 – 9261
		CPT 7		
0.25 – 2.2	5 – 40	490 – 3920	1323 – 10584	441 – 3528
2.2 – 4.5	40 – 112	3920 - 10976	10584 – 29635	3528 – 9878
		CPT 8		
0.25 – 2.0	5 – 40	490 – 3920	1323 – 10584	441 – 3528
2.0 – 4.6	40 – 110	3920 - 10780	10584 – 29106	3528 – 7202
		CPT 9		
0.25 – 2.6	5 – 40	490 – 3920	1323 – 10584	441 – 3528
2.6 – 4.5	40 – 116	3920 - 11368	10584 – 30694	3528 – 10231
		CPT 10		
0.25 – 2.2	5 – 40	490 – 3920	1323 – 10584	441 – 3528
2.2 – 4.5	40 – 116	3920 - 11368	10584 – 30694	3528 – 10231

CPT (cone penetration test)

3.3. Geoelectric Sections 2D along Traverses Interconnection

The geo-electric sections for all the VES in the area revealed three to four geo-electric layers. In all cases, the thickness of the 3rd or 4th layer could not be determined because the current electrodes spacing (AB/2) terminated at 200 m (Olorunfemi and Meshida (1987). The geo-electric section for VES 1 – 4 conducted along traverse AA’ stationed at 80, 100, 110 and 130 m respectively, revealed three to four geo-electric layers (Figure 5). When constrained with the borehole logs, the inferred lithology includes; topsoil (283–487 Ωm at 1.1 - 1.4 m), loose to fine sand (630–822 Ωm at 7.0 – 16.1 m) and medium dense, fine to coarse grained sand whose electrical resistivity values range between 100 and 179 Ωm.

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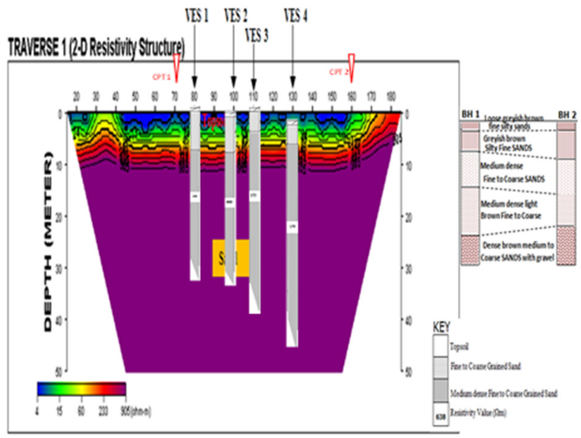

Figure 5: Selected CPT curves from the in-situ geotechnical measurement in the study area

The geo-electric section for VES 5 - 8 stationed at 80, 100, 110 and 130 m along profile 2 (Traverse BB') in Figure 6 revealed four geo-electric layers. The topsoil has resistivity range of 452 – 775 Ωm and thickness ranging between 1.0 – 1.2 m. The second geo-electric layer was interpreted as loose fine to coarse sand (1042 – 1132 Ωm) and has thickness values that range from 5.8 – 8.7 m within the depth range of 7.0 – 9.9 m respectively. The third geo-electric layer represented medium dense sand with resistivity values that vary between 100 - 179 Ωm. The geo-electric section generated along third traverse denoted as CC' from VES 9, 10, 11 and 12 were stationed at 80, 100, 110 and 130 m. The geo-electric layers delineated are topsoil of loose fine-grained sand (607 - 739 Ωm and 1.1 – 1.4 m). The next is loose fine to coarse sand layer (975 – 2544Ωm and 9.4 – 11.9 m), the third geo-electric layer represented medium dense sand (109–259Ωmand 45.6 – 57.9 m). The fourth layer constitutes dense fine to coarse sand and has resistivity values range of 1159 – 2531Ωm. 2D resistivity sections in this study represents the distribution of subsurface resistivity with depth along a total spread length of 200 m. The resistivity - depth model along this traverse reveals that the electrical resistivity of the topsoil ranges from about 5 to 24 Ωm and extends to depth of about 7 m beneath the subsurface (Dahlin, 1993). This low resistivity values could be as a result of the water lodge along the traverse. Below the topsoil down to depth of 50 m, the subsurface material is composed of sand with resistivity values that range from 233 – 905 Ωm and extends to 50 m depth. This layer can support foundation of engineering structure.

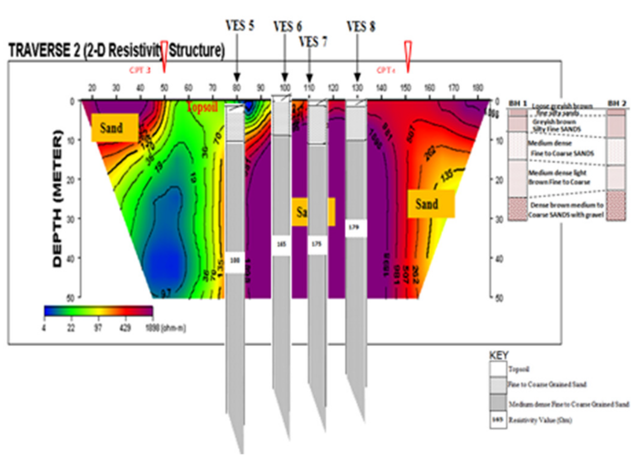

Figure 6: Selected CPT curves from the in-situ geotechnical measurement in the study area

The 2D resistivity section along traverse 3 is presented in Figure 7. The section is indicative of the distribution of subsurface resistivity with depth. The first geo-electric layer (top most layer) is composed of sand with resistivity values that range from 188 –1571Ωm and extends to depth of about 5 m beneath the subsurface.

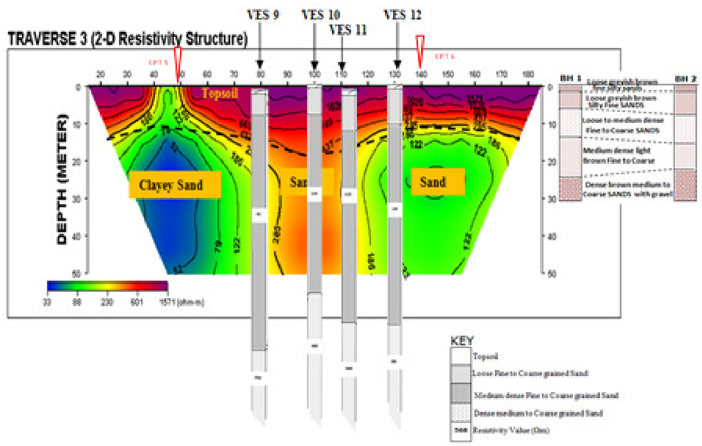

Figure 7: Selected CPT curves from the in-situ geotechnical measurement in the study area

The second geo-electric layer constitutes sand and correlate well with the borehole and VES results (Griffiths, and Barker, 1993). The resistivity of this layer ranges from 122 – 437Ωm and extends from about 5 – 15 m beneath the surface. The third geo-electric layer is composed of clayey sand and sand with resistivity values that range from 52 – 285Ωm and extends from about 15 – 50 m beneath the surface. The geo-electric section along DD' along profile 2, related VES 13 – 16 stationed at 80, 100, 120 and 140 m. The geo-electric section revealed topsoil (475 – 1128 Ωm and 0.9 – 1.2 m), loose fine to coarse grained sand. The second geo-electric layer (701–1268 Ωm and 2.1 – 11.4 m) is clayey sand. The third geo-electric layer (63 - 459 Ωm and 14.3 - 17.3 m) represents clayey sand/medium dense sand, while the fourth geo-electric (3482Ωm) layer beneath VES 15 is dense brown medium to coarse gained sand.

The 2D resistivity section along traverse 4 is presented in Figure 8. The section is indicative of the distribution of subsurface resistivity with depth. The first geo-electric layer (top most layer) is composed of sand with resistivity values that range from 429 –949 Ωm and extends to depth of about 6 m beneath the subsurface. The second geo-electric layer has resistivity values that ranges from 163 – 868 Ωm and extends from about 6 – 18 m beneath the surface. The third geo-electric layer is composed of clayey sand and sand with resistivity values that range from 57 – 330 Ωm and extends from about 13 – 50 m beneath the surface. The geo-electric section generated along EE' for traverse 5 includes VES 13 – 16 stationed at 80, 100, 120 and 140 m. The first geo-electric layer represents the topsoil with resistivity and thickness values that vary between 676 – 756 Ωm and 1.0 – 1.1 m. The second geo-electric layer was delineated within the depth that vary between 13.0 – 15.3 m with resistivity and thickness values that vary between 226 - 300 Ωm and 12.0 – 14.1 m beneath the surface. This layer constitutes loose fine to coarse grained sand. The third geo-electric layer represents clayey sand/medium dense fine to coarse grained sand with resistivity values that vary between 81–127 Ωm.

The 2D resistivity section along traverse 5 is presented in Figure 9. The section is indicative of the distribution of subsurface resistivity with depth. The first geo-electric layer (top most layer) is composed of sand with resistivity values that range from 1344 –215 Ωm and extends to depth of about 3m beneath the subsurface. The second geo-electric layer has resistivity values that ranges from 204 – 839Ωm and extends

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from about 3 – 16 m beneath the surface. The third geo-electric layer is composed of clayey sand and sand with resistivity values that range from 80 – 204 Ωm and extends from about 12 – 50 m beneath the surface.

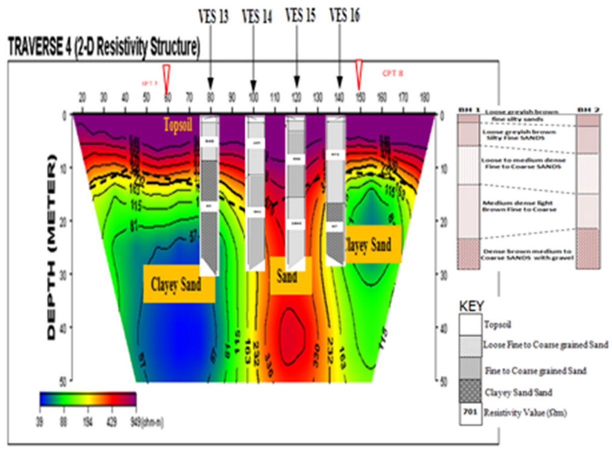

Figure 8: Selected CPT curves from the in-situ geotechnical measurement in the study area

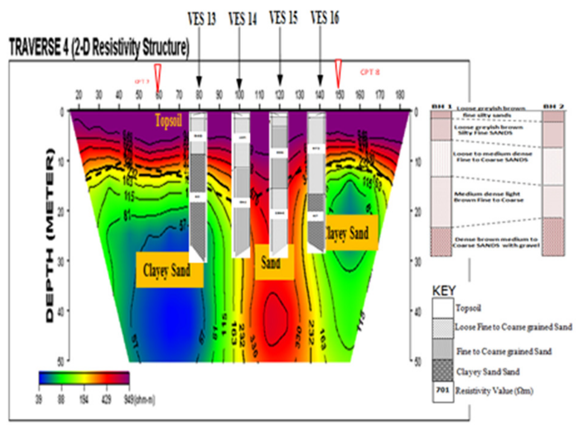

Figure 9: Selected CPT curves from the in-situ geotechnical measurement in the study area

4. CONCLUSION

The site investigation involving the use of electrical resistivity technique and penetration testing at Westwood Development Estate, Sangotedo, Lagos State, Nigeria was done. This revealed, number of different subsurface soil layers, their thicknesses and depth to competent foundation layers. Qualitative interpretation of both methods delineated subsurface soil layers and the borehole logs revealed in most cases topsoil, very loose fine to coarse grained sand, loose to medium dense sand and dense fine to coarse grained sand. Geophysical results revealed four geo-electric layers with the topsoil having electrical resistivity values that range from 283 to 1128 Ωm. The second layer is composed of loose fine to coarse grained sand and its thickness ranges between 2.1 and 16.1 m within the depth range of 3.0 and 17.4 m. The third layer was delineated within the depth range of 17.3 – 68.2 m comprises medium dense fine to coarse grained sand/clayey sand. The fourth layer is dominated by dense medium to coarse grained sand. In general, the geoelectrical pseudosections for the apparent resistivity distribution are direct reflections of the grain size of the subsurface soils. These are further supported by penetration resistance curves patterns and the respective allowable bearing capacity values. The top layer in the study area is inimical to foundation of any structure and required excavation to depth of about 1.4 m. Foundation moderate structures such as bungalows and a storey building can be accommodated by soils at depth of 3.0 m. However, deep foundations are recommended at greater depth for medium to high rise structures in the area.

5. CONFLICT OF INTEREST

There is no conflict of interest associated to this work.

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