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The use of Geoeletric Methods for Post-foundation Assessments of Distressed Buildings in Ebute-meta, Mainland Local Government Area of Lagos State

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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ABSTRACT

Geophysical and geotechnical investigations were combined to investigate the immediate causes of the distresses and foundation failures of buildings in Ebute-Meta area of Lagos, south-west Nigeria. Six (6) traverses were mapped in the study area across which six (6) 2D Wenner ERI, and fourteen (14) VES geophysical data were acquired. One (1) boring and five (5) CPT geotechnical data were also acquired. 2D ERI results reveal that resistivity values vary from 4.62 – 293 Ωm across the study area. Three resistivity structures were identified which denoted peat/clay, sandy clay, clayey sand and sand. The resistivity of the peat/clay varies from 4.62 – 27.9 Ωm with thickness varying from 12 - 25 m. The sandy clay varies in resistivity and thickness values from 26 – 86 Ωm and 8 – 29 m respectively. The clayey sand from 84.4 – 182 Ωm and 10 -15 m, and sand, having resistivity and thickness values of 293 Ωm and 3 – 5 m. The VES reveals similar results to the 2D ERI, delineating six geoelectric layers which are the topsoil, peat, clay, sandy clay, clayey sand and sand at maximum depth of 35.8 m. The borehole (BH) reveals a maximum boring depth of 45 m with eight zones comprising dark grey sandy clay, firm to stiff silty clay, soft, dark organic silty peaty clay, grey silty sand, dark grey silty sandy clay, dark grey organic peaty clay, grey silty sandy clay and medium dense to dense grey sand with occasional gravels. The CPT, which penetrated a maximum depth 15.8 m reveal that the cone resistance values vary progressively from 0 – 162 kg/cm^2indicating very soft clay to soft clay near-surface and medium dense to dense geologic material at deeper depth.

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The peat/clay delineated by the 2D ERI and VES at 5 – 25 m depth with resistivity value varying from 4.62 -17 Ωm in the study area, and also revealed in the BH at 5.75 – 27.75 m depth as soft, dark organic silty peaty clay, having cone resistance values varying from 0 – 20 kg/cm^2 is laterally extensive and incompetent to support engineering foundation.

Keywords: Peat; resistivity; cone penetration test; differential settlements; foundation.

1. INTRODUCTION

The recurrent cases of building collapse havebecome a major source of concern in Nigeria in recent time. The enormity of the losses in terms of lives and properties are becoming worrisome. The collapse is mostly experienced in cities of Lagos, Abuja and Port Harcourt -among the existing structures and those unde rconstruction [1]. These structural failures are often times associated with the problem of poor quality of building materials, old age of buildings and improper foundation [2].Foundations are affected not only by design errors but also by foundation inadequacies such as sitting them on incompetent earth layers. When the foundation of a building is erected on less competent layers, it poses serious threat to the building which can also lead to its collapse [3,4].Apart from the likely presence of incompetent layerssuch as soft, young clay or peat, faults, fractures or cavities could also be present all of which are inimical to superstructures. A propersite investigation will help to determine the nature and properties of the sub surface conditions. For engineering structure to have a long life span and provide safety for lives and properties, adequate preconstruction investigation must be carried out to locateand assess the strength and competency of the subsurface host materials.

Cracking, tilting and sinking in engineering structure are common failures that occur in most buildingspost-construction that arelocated in problematic areas. Building cracks commonly occur due to resultant differential settlement in the subsurface. The size, shape, pattern and location of cracks on a building, when compared with other sites and construction conditions can help to distinguish the probable causes of foundation based failures [5]. Seasonal volumetric changes in certain types of soil are the major factors affecting buildings' stability in most parts of the world. Certain clay soils can swell if they get saturated and when there is loss of water in them, they shrink drastically. These expansions and shrinkages of clayey soils can result to cracks on buildings even shortly after they are constructed [6]. A building component develops cracks whenever stress in the component exceeds its strength [7]. Cracks are classified into structural and non-structural cracks. The structural crack is due to faulty design, faulty construction or overloading which may endanger safety of buildings. The non-structural cracks are due to internal induced stress depending on the width of crack and these are classified into thin (< 1 mm), medium (1 mm – 2 mm), and wide (> 2 mm) [7]. Tilting and sinking of buildings are due to differential and uniform settlements respectively, of the subsurface earth materialson which the foundation is emplaced. The closeness of static water level to the foundation beds could also precipitates foundation instability [8]. Structural failures damage properties and endanger the lives in the environment; it can also stop the economic activity in the vicinity [9].

Engineering geophysics could be described as a discipline that stands between engineering geology and soil mechanics. It involves the application of geophysical methods to civil engineering projects.It is frequently used in pre- and post-construction investigation to determine subsurface ground conditions prior to excavation and construction work. Engineering geophysics therefore gives detail information on the degree of competence of the subsoil in foundation engineering. Geotechnical engineering practice requires investigation of soil and subsurface of the study site for engineering construction. This is done to ascertain the suitability of the earthmaterials at such site for structure in terms of bearing capacity.The use of Geophysical Techniques, such as electrical resistivity method (VES) or seismic method in engineering geophysics and the direct probing using static or dynamic penetration techniques and or boreholes are the different approaches commonly used toascertain the *in-situ* geo-mechanical properties of the soil [10]. The success in the applicability of geophysical techniques depends on so many factors. The most important is the existence of a significant and detectable contrast between the physical properties of the different units in the subsurface, such as velocity, electrical resistivity, conductivity, density, acoustic properties, subsurface geology and the environmental conditions. Penetration devices produce little overall disturbance in the soil. The most widely used static and dynamic penetration test are the Cone Penetration Test CPT (for soft soils) and the Standard Penetration Test SPT (for relatively hard soils) [11].

For CPT, a cone at the end of a series of rods is pushed into the ground at a constant rate, and measurements are made of the resistance to the penetration of the cone. This is known as “cone resistance” or qc, which is the total force (Qc) acting on the cone divided by the projected area (Ac) of the cone. The cone resistance qc isa direct indicator of the strength of the soil at a given depth. Cost, efficiency, speed, simplicity, reliability, andthe ability to provide near continuous information on the soil properties with depth are the important reasons for the increasing popularity of CPT [10]. The primary significance of CPT comes from the fact that it represents aminiature driven pile or foundation in soil; hence, the pilebearing capacity (pressure between a foundation and thesoil which will produce shear failure in the soil) can be directly estimated from qc. Thus, CPT provides valuableconstraints for all settlement and stability calculations.CPT qc responds to soil changes within five to ten times the cone diameter (standard = 35.6 mm) above and below the cone. Although CPT provides valuable information as to the strength of the soil, the information is restricted to the CPT location [12].CPTs are commonly performed tens or hundreds of meters apart. Soil models based on lateral in terpolationof CPT data collected at a few locations at a given site obviously contain large uncertainties, increasing the riskin engineering design. Engineering geophysics on the other hand has the potential to give 2D/3D laterally continuous but inferred sets of information having little or no uncertainty. Integration of the geophysical and the geotechnical approaches would reveal in true nature of the subsurface rock units.

The area of study is mainly a residential environment which borders a marsh. Most houses in the area are characterized by differential and uniform settlement shortly after construction. Cracks on the buildings are a common place in the area (Fig. 1).Geophysical and geotechnical methods were combined in the study area to determine from soil resistivity measurements, the nature of the soil and its suitability for building foundation, to determine the nature of the study area, to delineate the subsurface geological sequence and determine the geoelectric parameter, to identify existing subsurface geologic features such as faults/fracture and clayey/peat horizon that may be inimical to engineering foundations and may precipitates building instabilities and to investigate from the above probable causes of the distresses in the buildings in the study area.

Fig. 1. Distressed buildings in the study area showing settlements and cracks on the buildings

1.1 Geology and Location of the Study Area

The study area is underlain by the Coastal Plain Sand whichis made up of loose sediment ranging from silt, clay andfine to coarse grained sand. The littoral lagoonaldeposits are made up of clay, silt, and sands of coastalplains. The coastal belt varies in width from about 8 km near the Republic of Benin border to 24km towards the eastern end of the Lagos Lagoon [13] The age Oligocene to recent was assigned to this formation on the basis of fauna contents (Fig. 2). The study siteis located in Ebute-Meta, Lagos, Southwestern Nigeria. It lies within Longitudes; 3^{0}23’80” E - 3^{0}23’90” E and Latitudes; 6^{0}29’40” N - 6^{0}29’48” N. The studyarea is accessible through network of roads and footpaths.It is connected by many major and minor streets from Oyingbo, mainland Lagos. town Are town and Afao town. The topography is flat and low lying, gently sloping into the mars (Fig. 3).

2. MATERIALS AND METHODS

2.1 Data Acquisition and Processing

The data acquisition and processing involved geophysical and geotechnical sets of data.

2.2 Geophysical Investigation

The 2D electrical resistivity imaging (ERI) investigation and the 1D vertical electrical soundings (VES) were carried out using the PASI Terameter 16GL model along six traverse lines. The ERI profile lines were oriented in north-south and east-west directions with a traverse length of 200 m on traverse 1, 2, 3, 5 and 6 while traverse 4 is 100 m in length (Fig. 3). The data were acquired using Wenner electrode configuration (Fig. 4) with minimum and maximum electrode spread of 10.0 m and 60.0 m, respectively. The data obtained were processed and inverted using the RES2DINV software with a least-square inversion algorithm using a regularization technique [15]. A total of fourteen (14) VES points were distributed in the study area. The VES points were distributed across the traverse lines based on interpreted anomalous points on the traverse lines. On traverse one are VES 1, 2, 3 and 4, on traverse 2 are VES 5, 6, 7 and 8, on traverse 3 are VES 9 and 10, on traverse 4 are VES 11 and 12 and on traverse 5 are VES 13 and 14 (Fig. 3). Schlumberger electrode configuration was used for the VES and the maximum current electrode spread was 200 m. The data were partially curve-matched before been inverted using WINRESIST. The VES on each traverse were combined to generate the geoelectric section across each traverse.

2.3 Geotechnical Investigation

British standard, B.S 5930 (1999) was adopted for the boring, standard penetrometer test (SPT) and cone penetrometer test (CPT). One (1) hole designated asBH1 was bored on traverse 4 within the study area to a depth of 45 m using percussion boring method. VES 11 is parametric to the point of boring on the traverse. The boring involves the use of shell and auger tools to cut through the soil strata to the total depth of boring. Disturbed soil samples were collected at every 75 mm. Also, undisturbed samples were collected in the cohesive soil using a 100 mm internal diameter open tube sampler fitted with a cutting shoe. The SPT was conducted in cohesion-less soil using a thick-walled split spoon that was about 35 mm in internal diameter driven into the soils through several blows from 65 kg hammer falling from about 760 mm height. The resistance “N” value of the SPT shows the empirical evaluation of the soil’s consistencies; it is used to assess the strength, bearing capacity and compressibility of the granular soil. The collected soil samples were well preserved and transferred to the laboratory for further testing. In addition, a 2.5 ton cone penetrometer testing (CPT) was equally used tomeasure the in-situ strength of the soil within the study area. A total number of five (5) CPTs denoted as CPT 1-5 were carried out within the area of study along the traverses. Along traverse one are CPT 1 and 2 to which VES 1 and 4 are parametric respectively (Fig. 3). On traverse 2 is CPT 3 and to which VES 8 is parametric. On traverse 6 are only CPT 4 and 5 (Fig. 3).

3. RESULTS AND DISCUSSION

3.1 Geophysical Investigation

This involves the discussion of the geophysical results (2D and VES).

3.2 2D Resistivity Investigation

The inverted 2D resistivity models across the six traverses show that along traverse 1, 2, 3, 5 and 6, a lateral distance of 200 m was covered and a depth of 31.9 m is imaged on each of the traverse, while across traverse 4, a lateral distance of 100 m was covered and a depth of 15.9 m is imaged. Resistivity varies from 4.62 – 293 Ωm across the six traverses.

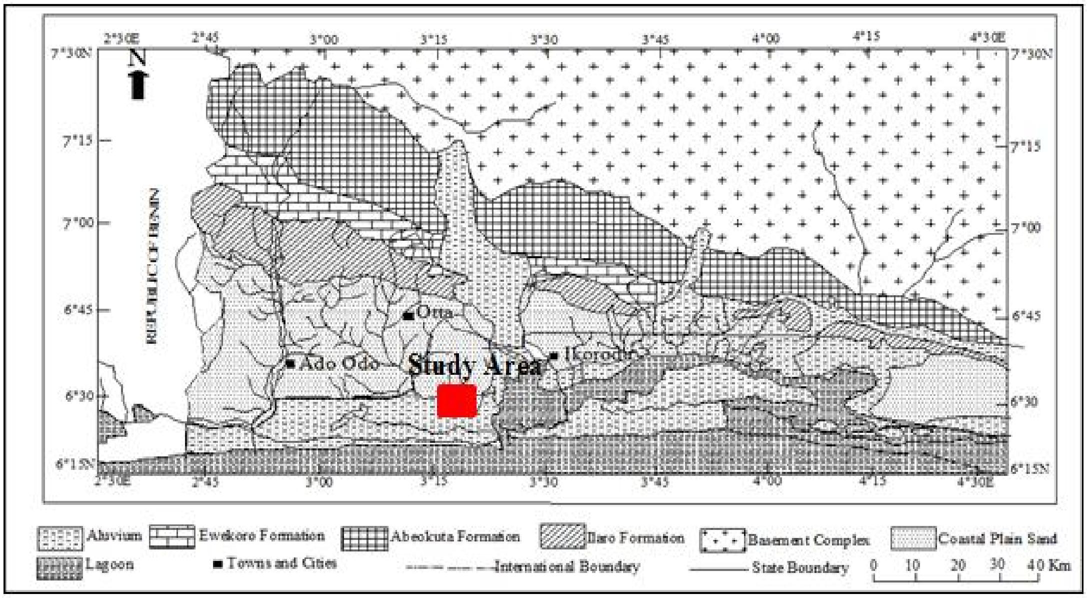

Fig. 2. Geological Map of Lagos State [14]

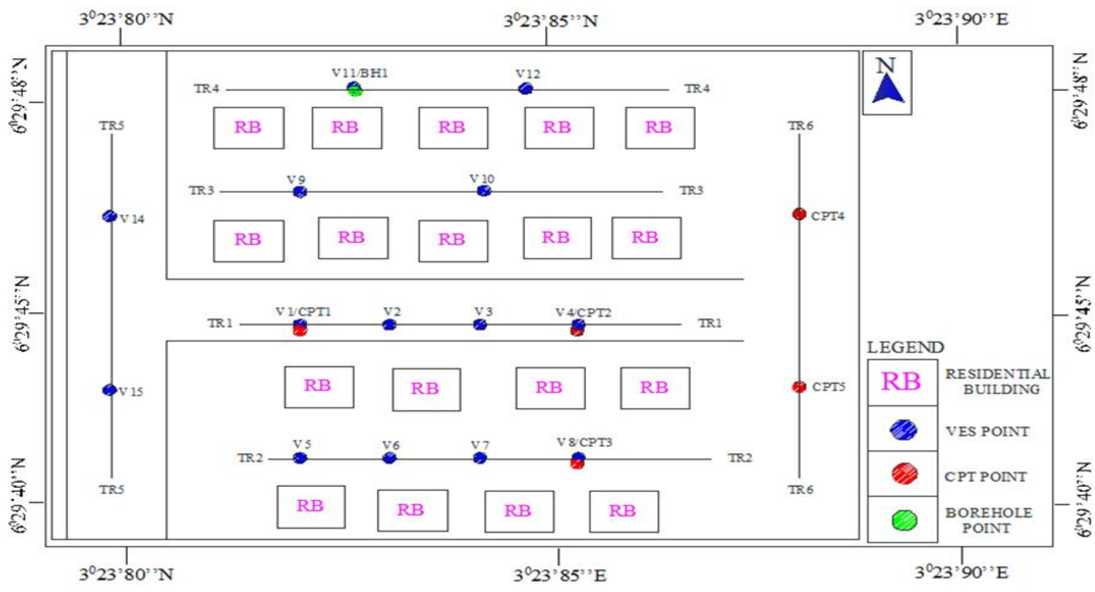

Fig. 3. Base map of the study area

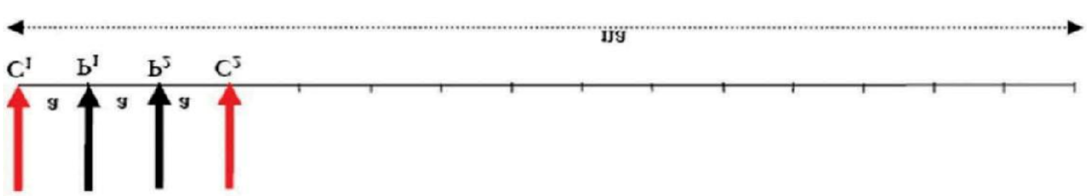

Fig. 4. Wenner array for2D ERI data measurements

On traverse 1 and 2, resistivity varies from 8.17 – 177 Ωm, indicating three subsurface resistivity structures which are peat/clay (with resistivity values ranging from 8.17 – 20.6 Ωm), sandy clay(26.3 – 75 Ωm)and clayey sand(84.4 – 177Ωm) (Figs. 5 and 6). The sandy clay occurs from the surface to a depth of 8 m and also occurs at about 24 – 29 m depth across the two traverses, thus sandwiching the peat/clay at depth ranging from 8 –24 m. Underlying the basal sandy clay is the clayey sand at depth of 29 – 31.9 m across the traverses. The peat/clay stratum which occurs from a depth of about 8 m across the entire two profile in the study area are incompetent material on or into which foundation of engineering structures could be emplaced. The peat/clay is prone to being differentially or uniformly settle on imposition of structural load. This stratum and the absence of denser lithology such as sand across the profile length, within the depth range of investigation are suspected to be responsible for the distresses on the building structures along the traverses in the study area (Figs. 5 and 6).

On traverses 3, 5 and 6, resistivity values vary from 6.08 – 182 Ωm which indicate three resistivity structures that are peat/clay having resistivity values ranging from 6.08 – 27.9 Ωm, sandy clay (28.8 – 86 Ωm) and clayey sand (98.1 – 182 Ωm). Across the three traverses, there are indications of non-uniform/non-layered heterogeneity (Figs. 7, 9 and 10) compared to traverse 1 and 2 (Figs. 5 and 6). The fact that these geoelectric units are incompetent to support engineering foundation, the high heterogeneity of the geoelectric units makes the foundation vulnerable to quick differential settlement. It is important to note that along traverse 3 and 5, the peat/clay stratum occurs deep-seated at about 24 – 31.9 m depth and fairly extensive laterally (Figs. 7 and 9). This is so unhealthy for the building foundations along these traverses and these are suspected to be responsible for the uniform sinking of the buildings in this area.

On traverse 4, resistivity values vary from 4.62 – 293 Ωm with three resistivity structures which reveal peat/clay with resistivity value varying from 4.62 – 15.1 Ωm, sandy clay (27.3 – 49.4 Ωm), clayey sand (89.4 – 162 Ωm) and sand (293 Ωm) (Fig. 8). The peat/clay is surficial, laterally extensive across the whole traverse and occurs from the surface to the maximum depth imaged in most part on the traverse (Fig. 8). The peat/clay is underlain by sandy clay and the clayey sand which are relatively thin. These are underlain by the sand at about 12 – 15.9 m depth. The occurrence of the thick peat/clay near surface and as well deep seated is no-doubt responsible for the distresses on the buildings along the traverse.

3.3 1D Vertical Electrical Sounding (VES)

The results of the VES across the entire study area are presented in Table 1. Resistivity values vary from 4.6 – 1033.1 Ωm. Six geoelectric layers are delineated which are the topsoil, peat, clay, sandy clay, clayey sand and sand. A maximum depth of 35.8 m is delineated.

On traverse 1 are VES 1, 2, 3 and 4 respectively which delineate topsoil with resistivity and thickness values of 14.5 – 31.6 Ωm and 0.6 – 0.8 m respectively, peat with resistivity and thickness of 8.7 Ωm and 15.1 m respectively, clay with resistivity and thickness values of 11.2 – 22.7Ωm and 2.4 – 33.8 m, sandy clay with resistivity and thickness 27.7 – 45 Ωm and 1.3 – 4.1 m respectively, clayey sand with resistivity values ranging from 74.7 – 87.2 Ωm but the thickness values could not be determined because the probing current terminated at that depth. Also, sand occurs in VES 2 with resistivity value of 177.2 Ωm but the thickness could not be determined as discussed earlier (Fig. 11A).The thick clay and peat geoelectric units occurring between 5 and 35 m depth are inimical to engineering foundation (Fig. 11A). These results confirm the findings from the 2D resistivity section along traverse 1.

On traverse 2 are VES 5, 6, 7 and 8. These reveal the topsoil with resistivity and thickness values of 26.8 – 1033.1 Ωm and 0.8 m respectively. The clay has resistivity and thickness values ranging from 11.5 – 19.5 Ωm and 17.7 – 31.7 m, sandy clay with resistivity and thickness 33.8 – 67.2 Ωm and 1.1 – 3.1 m respectively, clayey sand with resistivity values ranging from 89.5 – 93.9 Ωm but the thickness values could not be determined.Sand occurs with resistivity values of 132.8 – 158.2 Ωm but the thickness could not also be determined (Fig. 11B). The thick and laterally extensive clay unit along the traverse is suspected to have been responsible for the compromise of the building foundations in the area (Fig. 11B).

On traverse 3 are VES 9 and 10, along which are delineated topsoil with resistivity and thickness values of 69.7 – 79.4 Ωm and 0.6 m respectively.

The clay has resistivity and thickness values ranging from 12.4 – 39.5 Ωm and 1.5 – 23.5 m, sandy clay with resistivity and thickness of 45.3 Ωm and 20.4 m respectively and clayey sand with resistivity value of 80.1 Ωm but the thickness could not be determined(Fig. 11C).

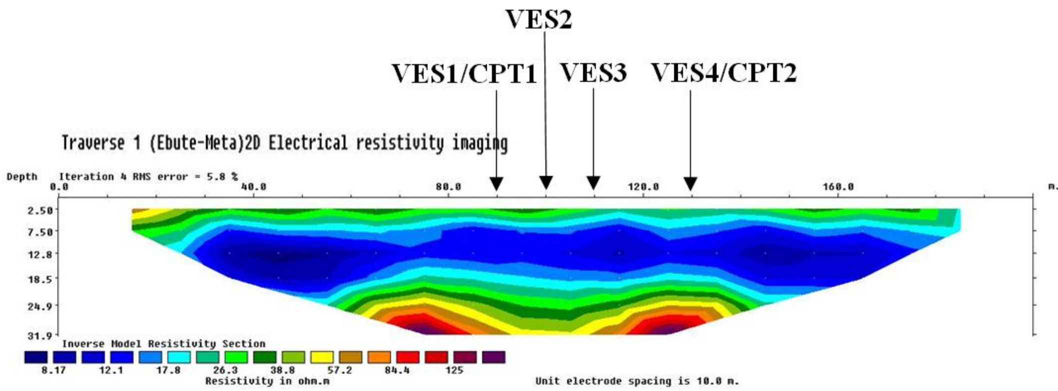

Fig. 5. 2D resistivity section along traverse1

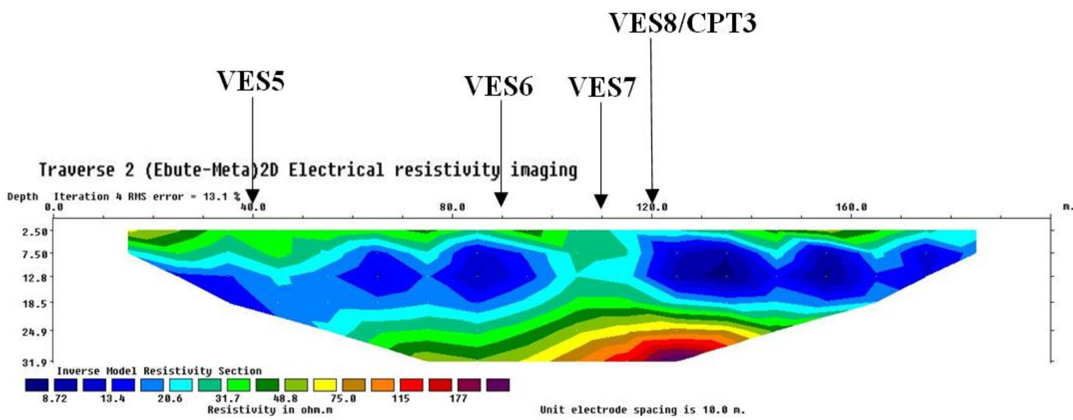

Fig. 6. 2D resistivity section along traverse 2

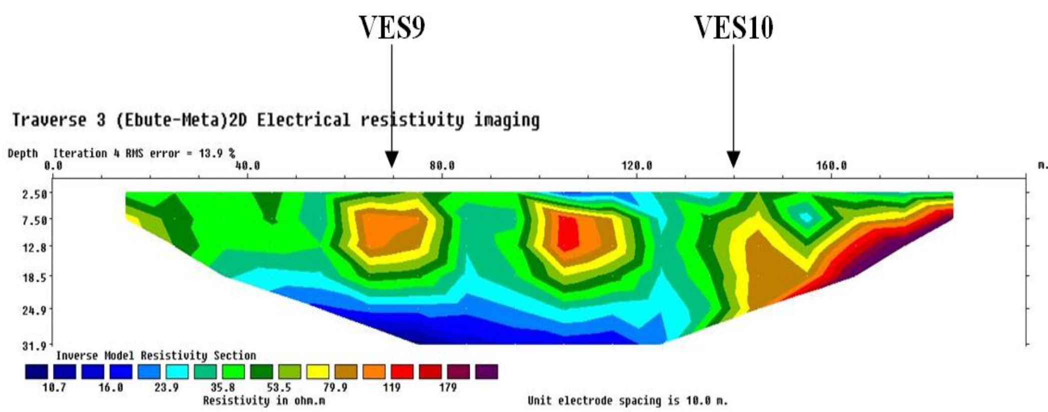

Fig. 7. 2D resistivity section along traverse 3

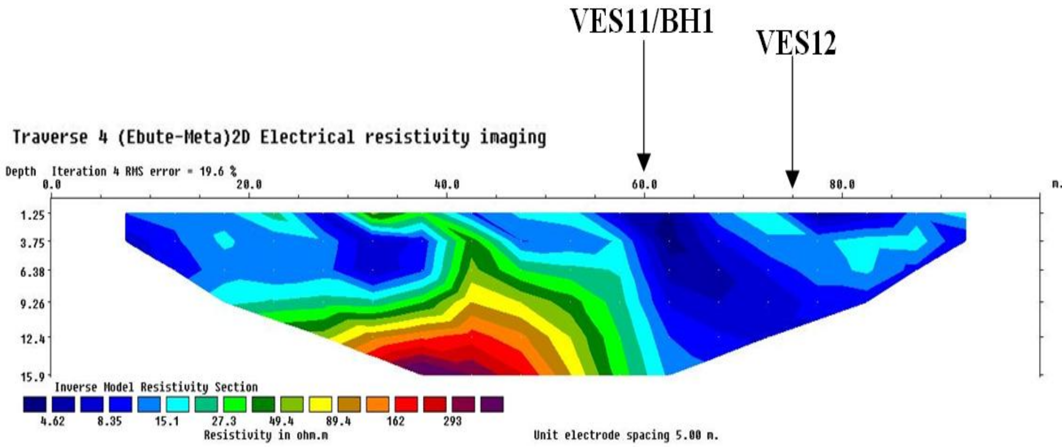

Fig. 8. 2D resistivity section along traverse 4

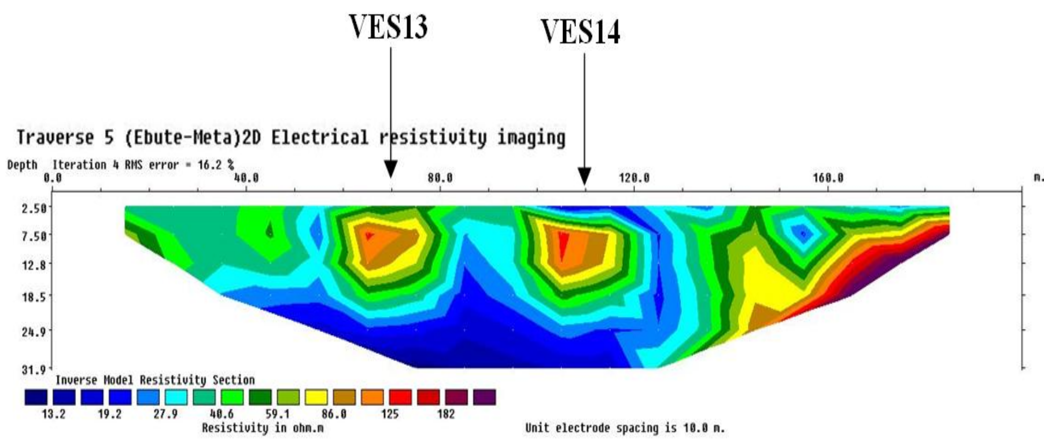

Fig. 9. 2D resistivity section along traverse 5

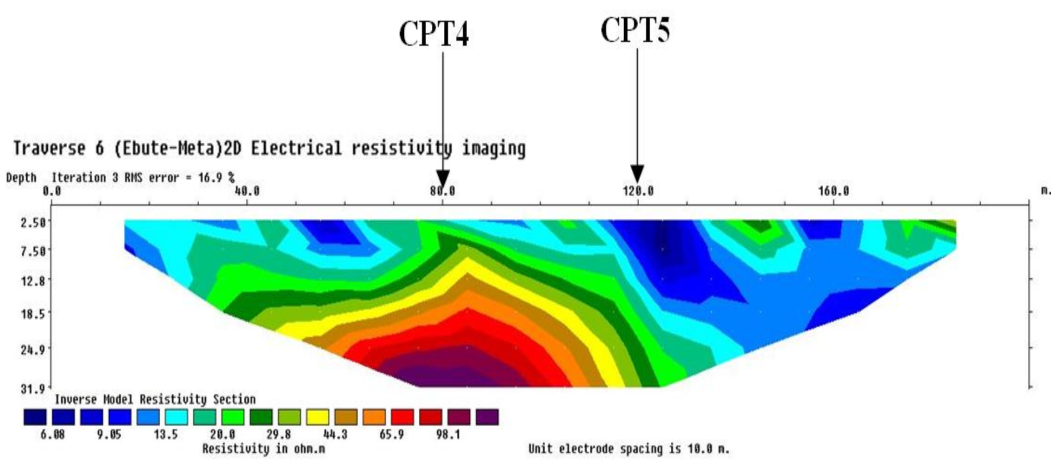

Fig. 10. 2D resistivity section along traverse 6

On traverse 4 are VES 11 and 12 which delineate topsoil, clay, peat and clayey sand. The topsoil varies in resistivity and thickness values from 55.9 – 100.8 Ωm and 0.7 m respectively, clay with 20.2 -20.8 Ωm and 2-3.4 m, peat, having 4.6 – 7.2 Ωm and 22.3- 32.8 m and clayey sand whose resistivity values vary from 36.1 – 47.3 Ωm but whose thickness could not be determined (Fig. 11D). The thick and laterally extensive column of peat, also overlain by clay is suspected to be responsible for the differential settlements that the foundation of the buildings have at present in the area.

On traverse 5 are VES 13 and 14 and along which are delineated topsoil, having resistivity and thickness values of 59.7 -74.2 Ωm and 0.5 – 0.6 m, clay with resistivity and thickness values varying from 17.1 – 23.3Ωm and 1.6 - 2.4 m respectively and clayey sand having 48.5 – 95 Ωm and 11.1 – 17.1 m respectively (Fig. 11E).

These results from the VES across the study area thus confirm the results from the 2D resistivity investigation along the traverses in the study area.

3.4 Geotechnical Investigation

This involvesthe discussion of the geotechnical results (Boring and CPT)

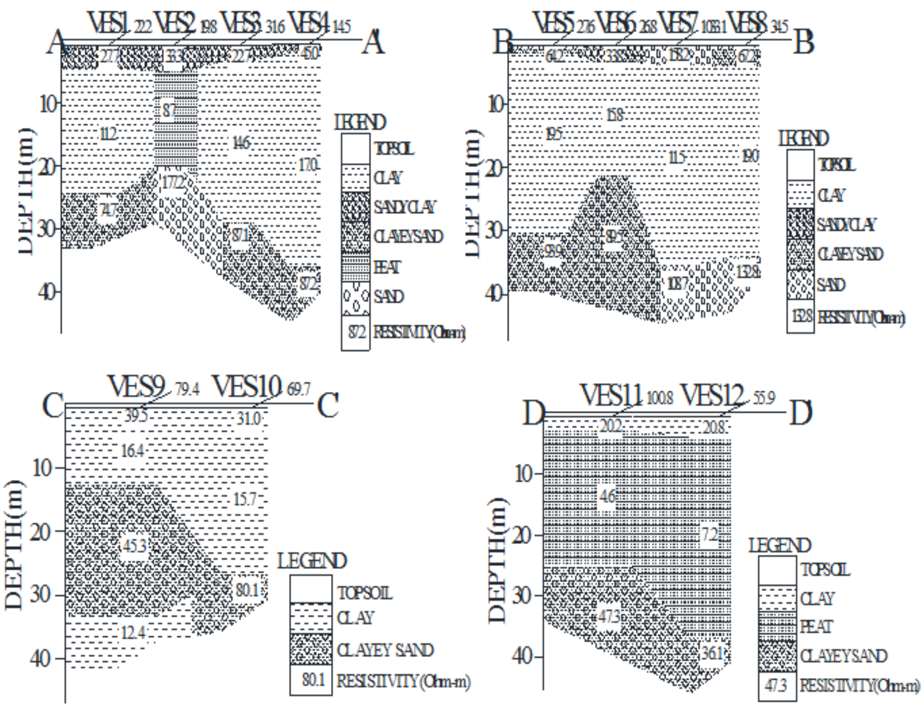

Fig. 11. Geoelectric section along traverse 1, 2, 3 and 4)

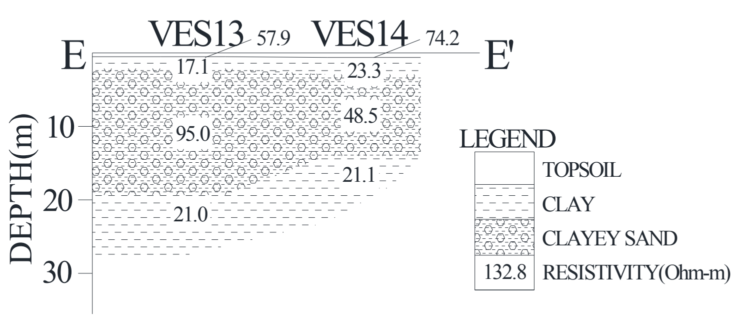

Fig. 11E. Geoelectric section along traverse 5)

Table 1. VES results

VES No	Layers	Resistivity (Ωm)	Thickness (m)	Depth (m)	Curve Type	Lithology
1	1	22.2	0.8	0.8	KH	Topsoil
	2	27.7	3.7	4.5		Sandy Clay
	3	11.2	19.5	24.0		Clay
	4	74.7	---	---		Clayey Sand
2	1	19.8	0.8	0.8	KH	Topsoil
	2	33.3	4.1	4.9		Sandy Clay
	3	8.7	15.1	20.0		Peat
	4	177.2	---	---		Sand
3	1	31.6	0.8	0.8	QH	Topsoil
	2	22.7	2.4	3.2		Clay
	3	14.6	25.5	28.7		Clay
	4	87.1	---	---		Clayey Sand
4	1	14.5	0.6	0.6	KH	Topsoil
	2	45.0	1.3	1.9		Sandy Clay
	3	17.0	33.8	35.8		Clay
	4	87.2	---	---		Clayey Sand
5	1	27.6	0.8	0.8	KH	Topsoil
	2	64.2	1.1	1.9		Sandy Clay
	3	19.5	28.5	30.4		Clay
	4	93.9	---	---		Clayey Sand
6	1	26.8	0.8	0.8	KH	Topsoil
	2	33.8	2.5	3.3		Sandy Clay
	3	15.8	17.7	21.0		Clay
	4	89.5	---	---		Clayey Sand
7	1	1033.1	0.8	0.8	QH	Topsoil
	2	158.2	3.0	3.8		Sand
	3	11.5	31.7	35.5		Clay
	4	108.7	---	---		Sand
8	1	34.5	0.8	0.8	KH	Topsoil
	2	67.2	3.1	3.9		Sandy Clay
	3	19.0	29.9	33.8		Clay
	4	132.8	---	---		Sand

VES No	Layers	Resistivity (Ωm)	Thickness (m)	Depth (m)	Curve Type	Lithology
9	1	79.4	0.6	0.6	QHK	Topsoil
	2	39.5	1.5	2.1		Clay
	3	16.4	10.6	12.7		Clay
	4	45.3	20.4	33.2		Sandy Clay
	5	12.4	---	---		Clay
10	1	69.7	0.6	0.6	KH	Topsoil
	2	31.0	2.6	3.2		Clay
	3	15.7	23.5	26.7		Clay
	4	80.1	---	---		Clayey Sand
11	1	100.8	0.7	0.7	QH	Topsoil
	2	20.2	2.0	2.7		Clay
	3	4.6	22.3	25.0		Peat
	4	47.3	---	---		Clayey Sand
12	1	55.9	0.7	0.7	QH	Topsoil
	2	20.8	3.4	4.1		Clay
	3	7.2	32.8	36.8		Peat
	4	36.1	---	---		Clayey Sand
13	1	59.7	0.5	0.5	HK	Topsoil
	2	17.1	1.6	2.1		Clay
	3	95.0	17.1	19.3		Clayey Sand
	4	21.0	---	---		Clay
14	1	74.2	0.6	0.6	HK	Topsoil
	2	23.3	2.4	2.9		Clay
	3	48.5	11.1	14.0		Clayey Sand
	4	21.1	---	---		Clay

3.5 Boring

The results of the borehole logs presents the ground-truth information of the sub-surface in the study area as shown in Fig. 12. The maximum borehole (BH) depth is 45 m. disturbed, undisturbed (piston), bulk, SPT and water samples were collected from the BH. Eight (8) zones are revealed in the BH1 (Fig.12). The log displays the stratification of soils and their description on the basis of types, colour and texture. The topmost layer reveals dark grey sandy clay from the surface to a depth of 0.75 m. This is underlain by a firm to stiff silty clay from a depth of 0.75 – 5.75 m (with a thickness of 5 m). Thefirm to stiff silty clay is underlain by soft, dark organic silty peaty clay from a depth of 5.75 – 27.75 m (having a thickness of22 m). At 27.75 – 30 m depth is the grey silty sand having a thickness of 2.25 m. Underlying the grey silty sandis the dark grey silty sandy clay from 30 – 31.25 m depth. Dark grey organic peaty clay underlies the dark grey silty sandy clay from 31.25 – 36 m depth and this overlies the grey silty sandy clay from 36 m depth to 39 m depth. Medium dense to dense grey sand with occasional gravels is encountered from 39 m depth to 45 m depth, which is the total drilled

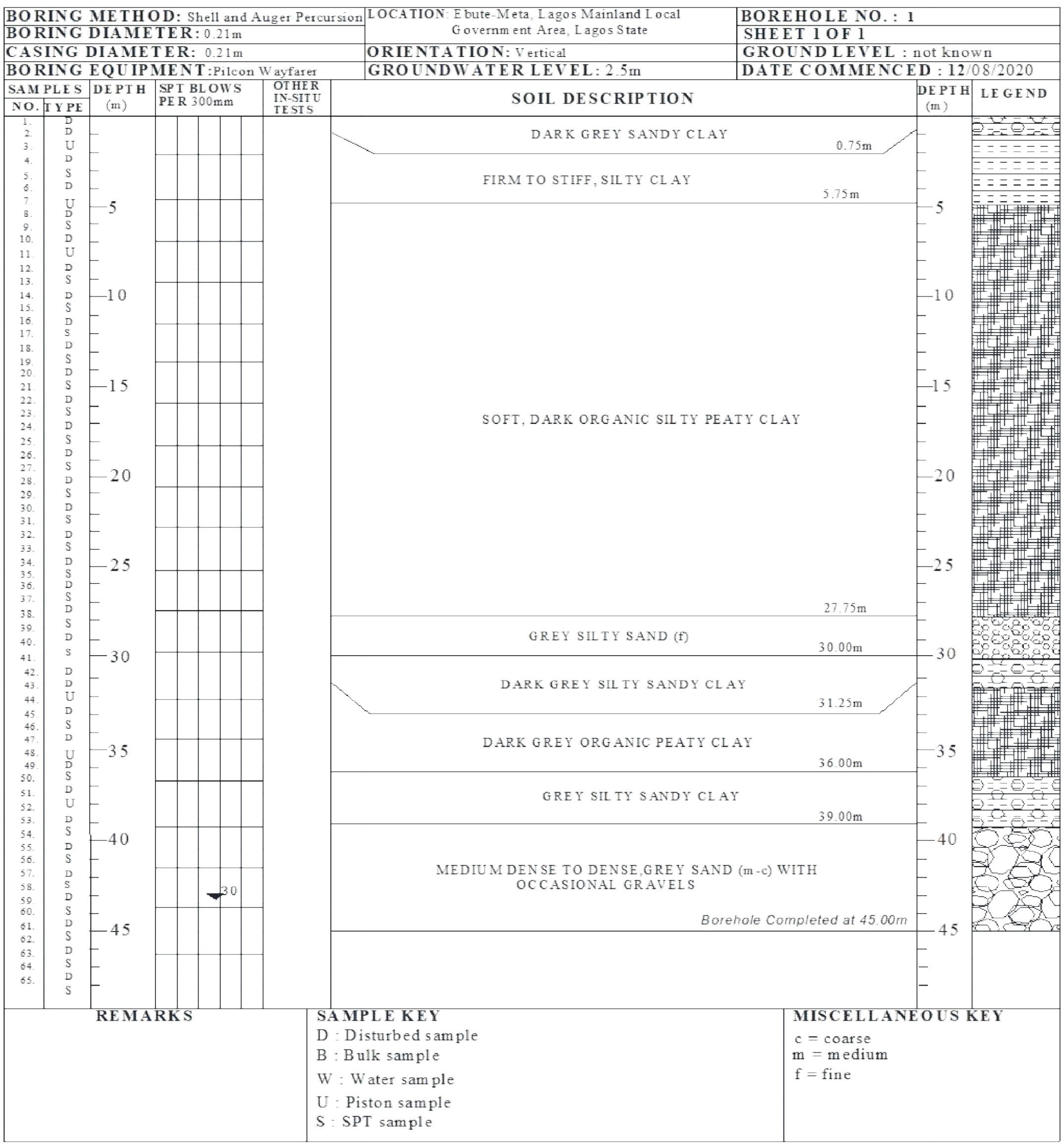

Fig. 12. Results of BH1 soil log stratification and description for the study area

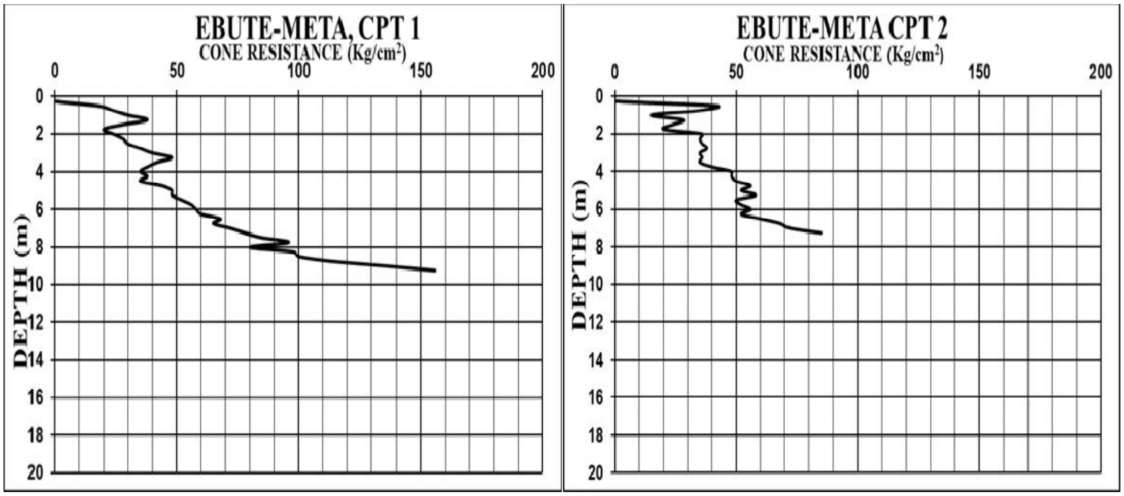

Fig. 13. CPT results along traverse 1

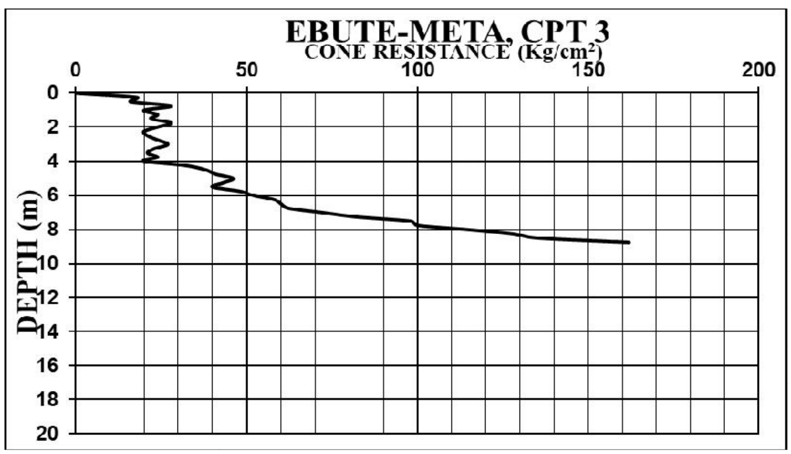

Fig. 14. CPT results along traverse 2

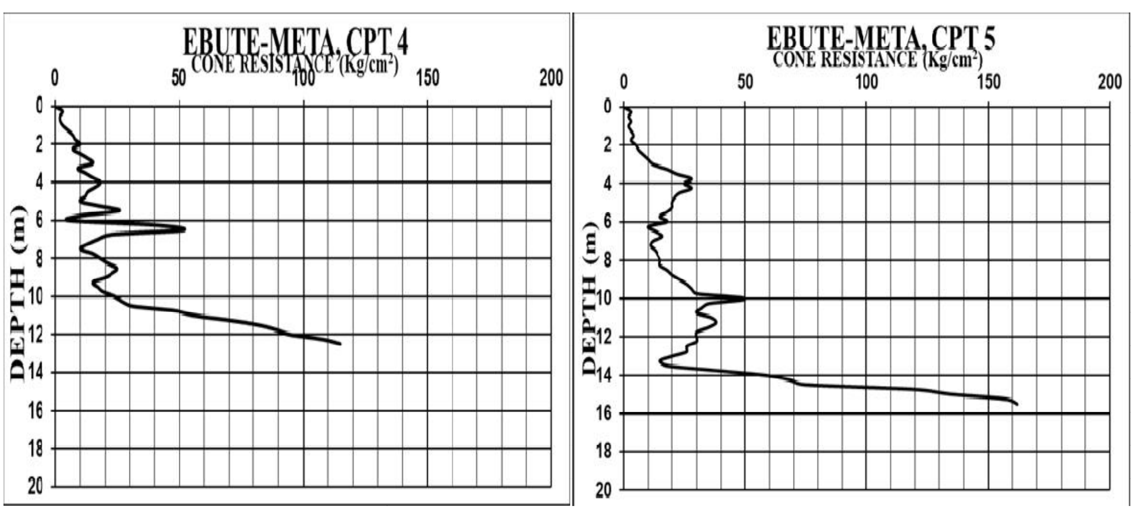

Fig. 15. CPT results along traverse 6

depth. This ground-truth BH information has revealed that the only geologic unit that could support engineering foundation in the study area is the densebasalsand that occurs from 39 m depth in the study area (Fig. 12). All overlying geologic units, from the surface to 39 m depth as revealed in the BH are incompetent to support engineering foundation in the study area. This no doubt has been responsible for the foundation distresses of the buildings in the localities in terms of cracking, differential and uniform settlements of the foundations. The overlying sandy clay, silty clay and peaty clay have the high potential to precipitate both differential and uniform settlements on emplacement of foundations on them. Pile foundation, which may transmit the foundation load to the dense sand below, is appropriate.

3.6 Cone Penetration Test (CPT)

Five (4) cone penetration tests (CPT) results conducted to determine the relative strength of the near-surface strata and also to assess the in-situ relative density of the soil in the study area are shown in Fig. 13, 14,15.

On traverse 1 are CPT 1 and 2. 7.8 m and 9.8 m depths were penetrated by CPT 1 and CPT 2 respectively. The cone resistance values range from 0 – 155 kg/cm^2. At 0.2 – 1.8 m depth, the cone resistance values progressively vary from 38 – 42 kg/cm^2. The values decrease to 20 kg/cm^2 from 1.8 to 2 m depth. The cone resistance progressively increases from 20 kg/cm^2 to 155 kg/cm^2 and 85 kg/cm^2 in CPT 1 and CPT 2 respectively from 2 – 9.8 m depth at both penetration points on the traverse (Fig.13).These cone resistance values (< 20 kg/cm^2) are indications of very soft clay to soft clay near-surface, while at deeper depth, the values (> 40 kg/cm^2) indicate medium dense to dense geologic material.

On traverse 2 is the CPT3 which is parametric to VES 8 (Fig. 6). A total depth of 8.8 m was penetrated and the cone resistance values vary from 0 – 162 kg/cm^2. The cone resistance values progressively increase from 0 – 20 kg/cm^2, from the surface to a depth of 0.5 m and then remains constant at 20 kg/cm^2 to a depth of 4 m. The cone resistance then progressively increases to 162 kg/cm^2 from 4 m depth to 8.8 m depth (Fig. 14). These values as well are indications of incompetent very soft clay to soft clay near-surface.

On traverse 6 are CPT 4 and CPT 5. Depths of 12.5 m and 15.8 m were penetrated in CPT 4 and CPT 5 and the cone resistance values range from 0 – 115 kg/cm^2 and 0 – 162 kg/cm^2 in CPT 4 and CPT 5 respectively. The cone resistance values are fairly constant from the surface to a depth of 2 m at 4 kg/cm^2(Fig. 15). The values then increase gradually from 4 kg/cm^{2}to 162 kg/cm^2.The values indicate dense earth materials at deeper depth while at near surface, there are indications of the soft clayey earth materials (Fig. 15).

4. CONCLUSION

Geophysical and geotechnical investigations involving 2D electrical resistivity imaging (ERI), 1D vertical electrical sounding (VES), Boring/standard penetration test (SPT) and cone penetration test(CPT) were carried out to investigate the immediate causes of the distresses and foundation failures of buildings in Ebutte-Meta area of Lagos, south-west Nigeria.

Six (6) traverses were occupied in the study area across which six (6) 2D Wenner ERI, and fourteen (14) VES geophysicaldata were acquired. In addition, one (1) boring and five (5) CPT geotechnical data were also acquired.

2D ERI results reveal that resistivity values vary from 4.62 – 293 Ωm across the study area and three resistivity structures are imaged which denote peat/clay, sandy clay, clayey sand and sand. The resistivity of the peat/clay varies from 4.62 – 27.9 Ωm with thickness varying from 12 - 25 m. The sandy clay varies in resistivity and thickness values from 26 – 86 Ωm and 8 – 29 m respectively. The clayey sand from84.4 – 182 Ωm and 10 -15 m, and sand, having resistivity and thickness values of 293 Ωm and 3 – 5 m. The VES reveals similar results to the 2D ERI, delineating six geoelectric layers which are the topsoil, peat, clay, sandy clay, clayey sand and sand at maximum depth of 35.8 m. The borehole (BH) reveals a maximum boring depth of 45 m with eight zones comprising dark grey sandy clay (at a depth range 0 - 0.75 m.), firm to stiff silty clay (at 0.75 – 5.75 m depth), soft, dark organic silty peaty clay (5.75 – 27.75 m), grey silty sand (27.75 – 30 m depth),dark grey silty sandy clay (30 – 31.25 m depth), dark grey organic peaty clay (31.25 – 36 m depth), grey silty sandy clay (from 36 - 39 m depth) and medium dense to dense grey sand with occasional gravels (at 39 - 45 m depth). The CPT results reveal that the cone resistance values vary progressively from 0 – 162 kg/cm^{2}indicating very soft clay to soft clay near-surfaceand medium dense to dense geologic material at depth andthe CPT penetrated a maximum depth 15.8 m. The peat/clay delineated by the 2D ERI and VES at 5 – 25 m depth with resistivity value varying from 4.62 -17 Ωm in the study area, and also revealed in the BH at 5.75 – 27.75 m depth as soft, dark organic silty peaty clay, having cone resistance values varying from 0 – 20 kg/cm^2 is laterally extensive and incompetent to support engineering foundation. This however is suspected to be responsible for the differential settlement, uniform settlement and the cracks that are prevalent in the buildings in the area. The geoelectric layer competentto support engineering foundation is the dense basalsand that occurs from 39 m depth in the study area. Only foundations sited on this dense sand is likely to be stable while foundations sited on all other incompetent overlying peaty/clayey earth units are vulnerable to be distressed by differential/uniform settlement sooner or later.

Pile foundation to a minimum depth of 40 m is recommended for subsequent development in the study area.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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