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Assessment of the Causes of Structural Defects Using Geophysical and Geotechnical Approach

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Abstract **Original Research Article**

The rate at which buildings are collapsing/distressing is alarming especially in Lagos, Nigeria where land is very limited in supply and it seems unabated. This incessant occurrence of building collapse is highly prevalent at Oke-Ira area of Lagos State, which informed the choice of the site as the study area. Geophysical and geotechnical methods were conducted to characterize the sub surface layers of the soil at the location to ascertain the soil profile and the possible causes of structural failures at the site. Six vertical Electrical Soundings, VES were employed using Schlumberger arrays and five Cone penetration tests, CPT were also carried out at the location. The result of the VES showed layers of top soil, silt, clay, peat and sand. The VES soundings indicated there was incompetent layer of peat/clay with resistivity ranges between 5.31 – 16.04Ωm with depth between 0.77 – 14.15m. This aligned with the result of CPT that showed the peat thickness to be between 0 - 12m. The investigations revealed that the study area was underlain by weak materials which progressively got stronger as the depth increased. This peat and soft clay have high compressibility, high void, and low load bearing capacity thereby unsuitable for foundation. The thickness of the peat layer is much, therefore, the usage of shallow foundation within the site location is precluded. But unfortunately, most structures around the study area had shallow foundations and this might be the possible cause of the structural failures noticed at the study area. However, deep foundation with piling up to 15m is recommended at the site.

Keywords: Geophysical, Geotechnical, Vertical Electrical Sounding (VES), Cone Penetration Test (CPT), Peat, Sand.

1. INTRODUCTION:

The rate at which buildings are collapsing/distressing is alarming especially in Lagos, Nigeria where land is very limited in supply and it's seeming unabated. The incessant occurrence of building collapse is highly noticeable at Oke-Ira area of Lagos State. Contrary to the believe of the Nigerian Institute of Engineers (NISE) that assumes that the major cause of collapsed building is structural failure, there are many causes of this problem, but the most fundamental cause is foundation failure. This foundation problem may be as a result of not using the right foundation type, using weak soil strata that do not have the strength/capacity to carry the load on it (low bearing pressure). Most builders fail to recognize that the soil surrounding a foundation is responsible for the majority of foundation failures. Even foundations built with good materials and first-class workmanship will fail if poor soil conditions are considered (Robert, 1996).

The ultimate aim of a subsurface investigation is to assess enough information to select the most appropriate foundation solution, to outline problem that could arise during construction and after and on a more general scale to highlight potential geological hazards in the examined area (Tomlinson, 1980).

Cases of distressed /collapsed buildings leading to structural failure at Oke-Ira, Gbagada, and Lagos have been on the increase. Most of the cases were not normally traced to the structures of the buildings, but to the problem associated with the foundations of the facilities.

The combination of geophysical (electrical resistivity) and geotechnical techniques is very useful in the investigation of subsurface composition and site characterization, as demonstrated empirically by Adeoti et al (2009).

An integrated geophysicalal and geotechnical approaches were used to assess and investigate the site characterization and mechanics of the study site in order to provide sufficient information regarding foundation construction, soil strata and bearing pressure, minimum and maximum load so as to avoid unnecessary structural failure in the future.

2. MATERIALS AND METHODOLOGY:

Materials

ABEM SAS 1000 Terrameter, Global Positioning System, GPS, Measuring tape, Metal electrodes, Reel cables, Hammer, A Dutch Static Penetration equipment, Anchors, Cone & tube, U-type sampler with cutter, Rods and Boring pipes.

Figure 1: ABEM SAS 1000 Terrameter and its accessories.

METHODS

Data Acquisitions

Geophysical Survey

In carrying out electrical resistivity survey, ABEM SAS 1000 Terrameter manufactured by ABEM AB of Sweden, alongside with battery (a 12V Lead-acid accumulator), one Global Positioning System (GPS), measuring tape, four metal electrodes, four reels of cables, three pieces of hammer, measuring tapes, were used for resistivity measurements. A minimum of 2 and maximum of 4 stacks measurement were adopted to ensure high signal/noise ratio. Six Vertical Electrical Sounding Stations were allotted at major points in the studied area. The geodetic system of coordinates was obtained using Garmin 12 Global Positioning System. The Schlumberger current electrode separation (AB) was varied from a minimum of 2.0m to a maximum of between 50 and 230m at the VES locations. The hammers were employed in driving the steel electrodes into the earth. The measuring tapes were used to measure out distances for the different electrode spacing.

GEOTECHNICAL SURVEY

Cone Penetration Tests were performed at a total five (5) locations within the study area. The Dutch static penetration measured the resistance of penetration into soils using a 60% steel cone with an area of 10.2cm^2. The test was carried out by securing the winch frame to the ground by means of anchors. These anchors provided the necessary power to push the cone into the ground. The cone and the tube were pushed together into the ground for 20 to 25 cm; the cone was pushed ahead of the tube for 3.5 cm at a uniform rate of about 2cm/s. The resistance to the penetration of the cone registered on the pressure gauge connected to the pressure capsule was recorded. The tube was then pushed down and the procedure described above was repeated.

DATA PROCESSING

RESISTIVTY DATA

The apparent resistivity measurements at each station were plotted against half current electrode spacing (AB/2) on bi-logarithmic graph sheets, using a transparent tracing paper superimposed on the log-log paper. The curves obtained were curve matched using a set of two layers modeling curves. The curves were inspected to determine the number and nature of the layering. Partial curve matching was carried out for the quantitative interpretation of the curves. The results of the curve matching (layer resistivities and thicknesses) were fed into the computer as a starting model in an iterative forward modeling technique using RESIST version 1.0 (Vander Velper, 1988). This was to vindicate the correlation of the field curve and the theoretical curves and from the interpreted results (layer resistivities and thicknesses), geoelectric section of each of the VES point was produced. WinGLink software was also used to interpret the resistivity data so as to verify the earlier interpretation done by master curves, auxiliary graph and RESIST software.

CONE PENETROMETER DATA

The cone penetrometer test is a means of ascertaining the resistance of the soil. The layer sequences were interpreted from the variation of the values of the cone resistance with depth. From the series of recorded gauge readings, cone resistance and sleeve friction were plotted against depth. In a nutshell successive cone resistance and sleeve resistance readings were plotted against depth to form a resistance profile using Microsoft Excel.

3. RESULTS AND DISCUSSIONS

Six vertical electrical soundings were occupied around the site alongside five cone penetrometer tests and an attempt to corroborate the results of the electrical resistivity sounding with the penetrometer was made.

A manual quantitative interpretation of the data set by partial curve matching and iterative inversion using the Win resist software, the generated curves beneath the VES stations were corrected for noise effect (smoothened) and interpreted using the WingLink software and summary of the interpretations were given in tables 1-6 and the generated curves were shown in figures 2-4

Five CPT were occupied around the site to a maximum depth of 16m using a 2.5ton Static Dutch Cone Penetrometer. The penetrometer was a fixed cone tip type capable of measuring point resistance and skin friction indirectly.

The cone has an apex angle of 60^0, diameter of 36mm and sectional area 10cm^2. For the purpose of this study, only the point resistance was measured on site; this practice is usual when making use of the 2.5ton Dutch Cone Penetrometer and is considered sufficient (Sanglerat, 1972). The data obtained were displayed in table 7.

The data were plotted on an arithmetic graph paper with cone resistance on the abscissa and depth on the ordinate. The plots are shown in figures 5-7.

Table1: Summary of interpretation at VES 1

VES 1			
Layer	**Resistivity (Ωm)**	**Depth (m)**	**Lithology**
1	34.02	1.79	Top soil
2	11.29	4.47	Clay
3	5.31	12.09	Clay / Peat
4	22.03	22.03	Silty Clay
5	147.30		Sand

Table 2: Summary of interpretation at VES 2

VES 2			
Layer	**Resistivity (Ωm)**	**Depth (m)**	**Lithology**
1	30.97	2.52	Top soil
2	13.16	10.62	Clay
3	20.81	13.97	Silty Clay
4	192.18	73.31	Sand
5	56.22		Sand

Table 3: Summary of interpretation at VES 3

VES 3			
Layer	**Resistivity (Ωm)**	**Depth (m)**	**Lithology**
1	13.54	0.94	Top soil
2	44.05	4.29	Silty Sand
3	11.53	14.15	Clay
4	84.59	37.60	Sand
5	213.85		Sand

Table4: Summary of interpretation at VES 4

VES 4			
Layer	**Resistivity (Ωm)**	**Depth (m)**	**Lithology**
1	17.10	0.77	Top soil
2	10.12	8.14	Clay
3	27.59	14.85	Silty Clay
4	77.00	42.74	Sand
5	369.44		Sand

Table 5: Summary of interpretation at VES 5

VES 5			
Layer	**Resistivity (Ωm)**	**Depth (m)**	**Lithology**
1	24.82	0.46	Top soil
2	16.04	3.32	Clay
3	34.88	10.01	Sandy Clay
4	54.94	27.85	Sand
5	825.40		Sand

Table 6: Summary of interpretation at VES 6

VES 6			
Layer	**Resistivity (Ωm)**	**Depth (m)**	**Lithology**
1	5.16	0.46	Top soil
2	11.54	1.60	Clay
3	8.42	7.51	Clay / Peat
4	661.96	19.95	Sand
5	406.20		Sand

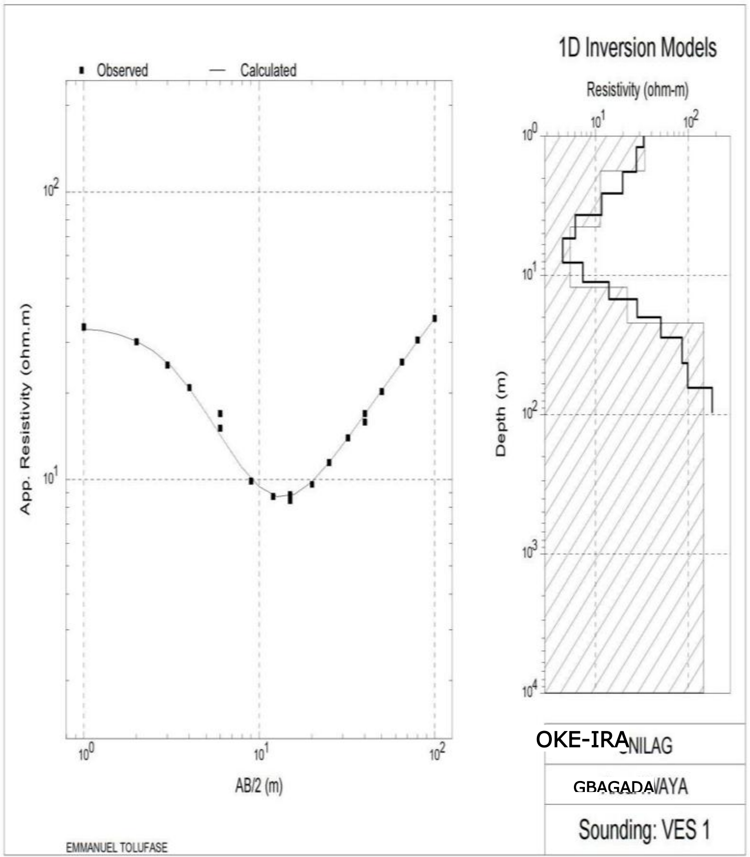


Figure 2: Sounding Curve and Geo-electric Section Obtained at VES 1

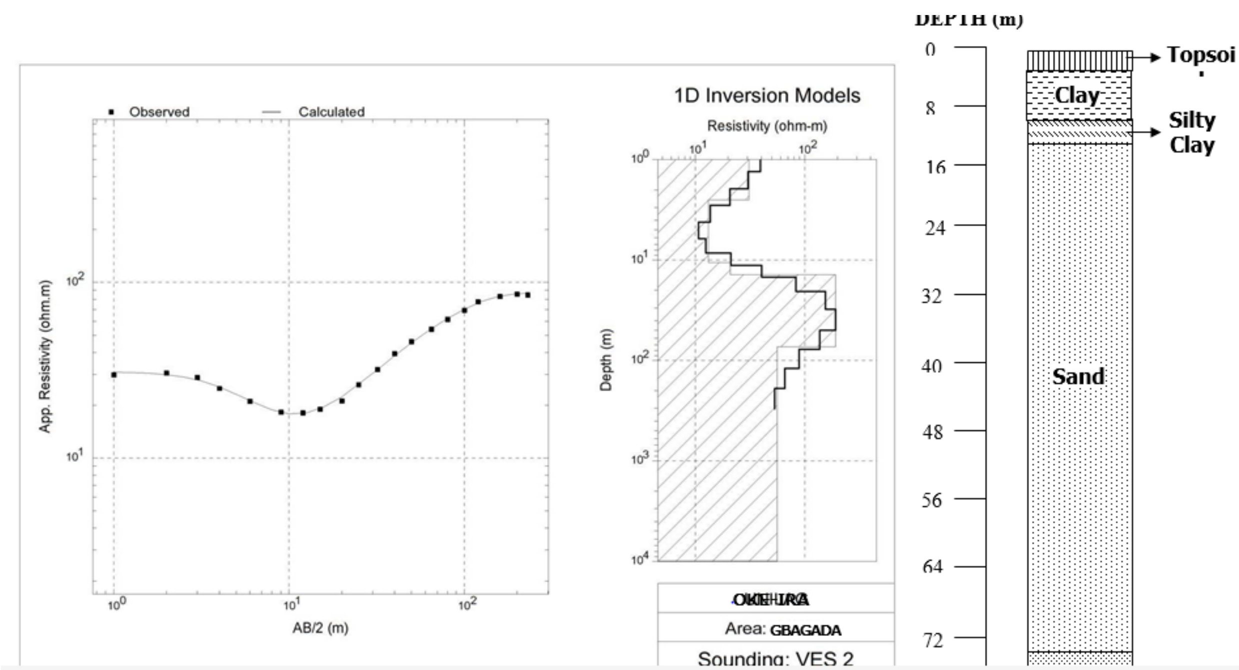


Figure 3: Sounding Curve and Geoelectric section obtained at VES 2

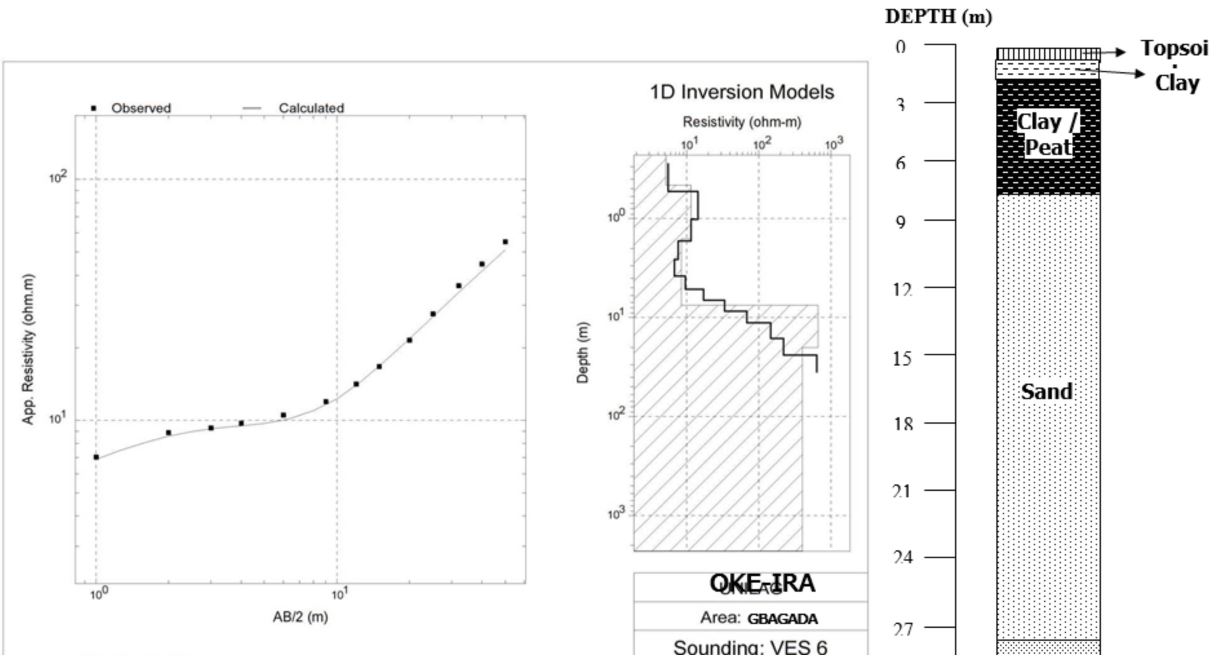


Figure 4: Sounding curve and geoelectric section at VES 6

TABLE 7: CPT Data

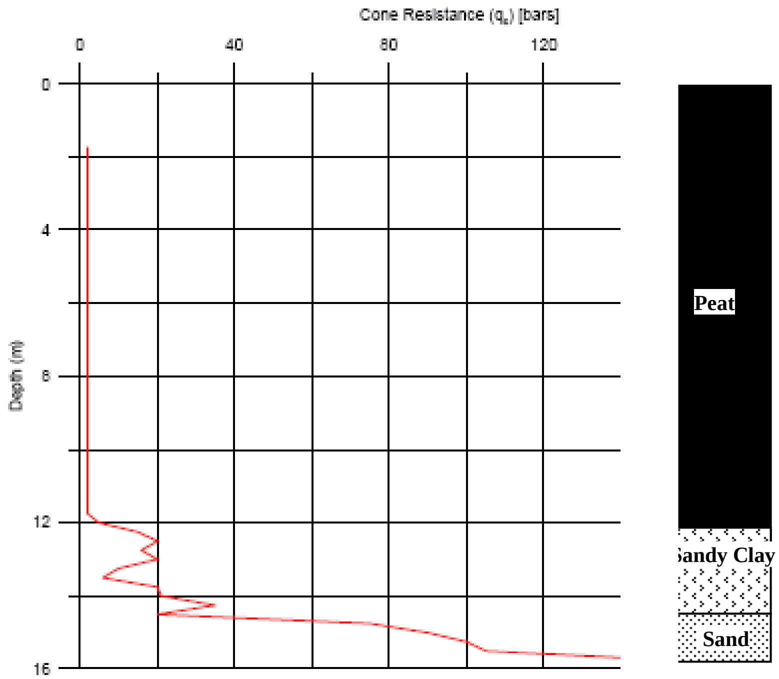
DEPTH (m)	CONE RESISTANCE (q_c) (bars)				
	CPT 1	CPT 2	CPT 3	CPT 4	CPT 5
0.25	1	2	2	2	5
0.50	2	2	2	2	10
0.75	2	2	5	2	15
1.00	2	2	2	2	5
1.25	2	3	2	2	20
1.50	2	2	2	2	25
1.75	2	2	45	2	30
2.00	2	2	2	2	35
2.25	2	2	2	2	35
2.50	2	17	2	2	40
2.75	2	2	2	2	25
3.00	2	2	2	2	35
3.25	2	2	2	2	40
3.50	2	2	2	2	40

3.75	2	5	2	2	35
4.00	2	7	2	2	30
4.25	2	7	2	2	35
4.50	2	2	2	2	40
4.75	2	2	2	2	30
5.00	2	2	2	2	35
5.25	2	2	2	2	45
5.50	2	2	2	2	50
5.75	2	2	2	2	65
6.00	2	2	2	2	70
6.26	2	2	2	2	35
6.50	2	2	2	2	40
6.75	2	2	2	2	55
7.00	2	2	2	2	60
7.25	2	2	2	2	45
7.50	2	2	2	2	45
7.75	2	2	2	2	50
8.00	2	2	2	2	65
8.25	2	2	5	5	75
8.50	2	2	7	10	80
8.75	2	2	8	15	80
9.00	2	5	10	15	65
9.25	2	45	10	10	65
9.50	2	50	10	12	85
9.75	2	50	9	15	95
10.00	2	60	10	20	100
10.25	2	80	12	10	100
10.50	2	85	10	15	115
10.75	2	95	20	20	120
11.00	2	95	25	25	150
11.25	2	100	30	25	
11.50	2	105	35	30	

11.75	2	115	40	40	
12.00	5	155	45	45	
12.25	15		60	60	
12.50	20		80	50	
12.75	16		100	80	
13.00	20		120	75	
13.25	10			90	
13.50	6			95	
13.75	20			100	
14.00	21			90	
14.25	35			90	
14.50	20			95	
14.75	75			100	
15.00	90			105	
15.25	100			95	
15.50	105			100	
15.75	150			115	
16.00	170			150	

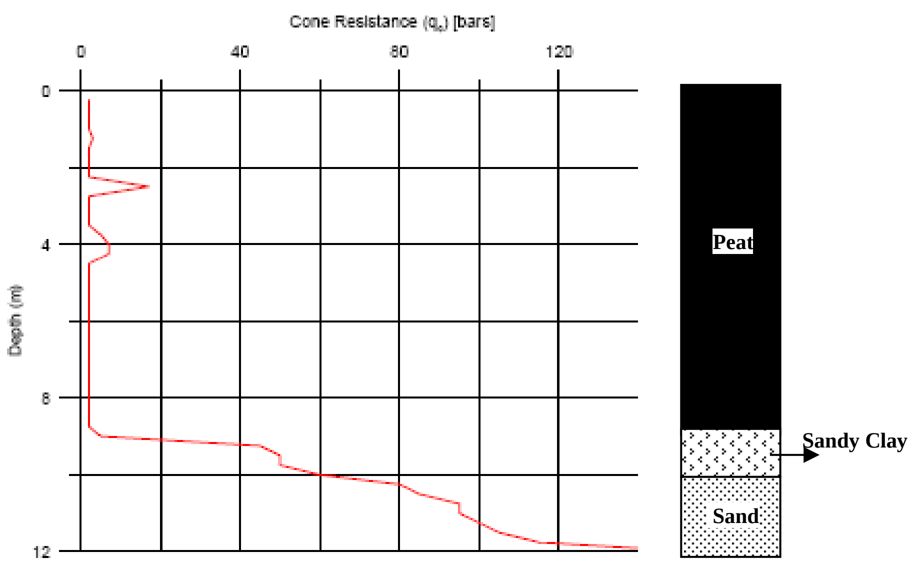
Table 8: Relation of Point Resistance to Soil Material (After Kerisel)

Point resistance, q_c	Soil material
50 – 300 bars or more	Sands
< 60 bars	Silts
< 30 bars	Medium clays
< 10 bars	Soft clays or peats



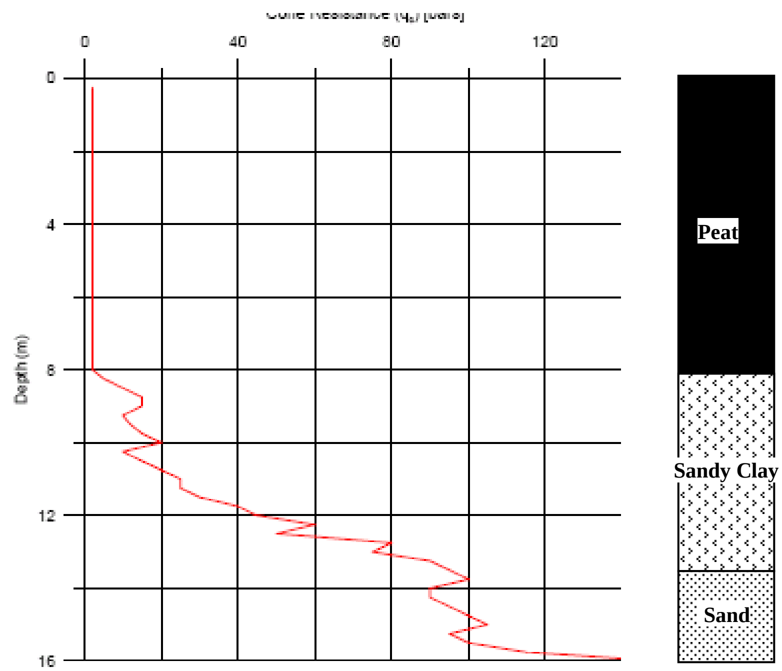
CPT 1

Figure 5: A graph of depth against resistance Q_c



CPT 2

Figure 6: layers of the soil as shown by CPT2



CPT 4

Figure 7: layers of the soil as shown by CPT 4

GEOELECTRIC SECTIONS

The geoelectric sections from VES 3 and 4 were made up of five geoelectric layers. The first three layers showed low resistivity values which range from 10.12-44.05Ωm with thickness varying from 0.77-14.15m from the surface. This low resistivity is inferred to be Clay/peat.

And the remaining fourth and the fifth layers have moderate values of resistivity which varied from 77.00-369.44Ωm whose thickness also ranged from 37.60-42.74m. The resistivity values within the range inferred Sand.

The VES 5 and 6's first layer, topsoil, was characterized by low resistivity values which were 5.16 and 24.82Ωm respectively. Its respective thickness was 0.46m. The second substratum inferred clay of resistivity 11.54 and 16.04Ωm with thickness1.60m and 3.32m respectively. The third layer was inferred Sandy clay for VES 5 of resistivity 34.88Ωm and thickness 10.01m but VES 6 was inferred to be clay/peat with resistivity 8.42Ωm and thickness 7.51m. The fourth and the fifth layers were inferred to be Sand for both VES 5and 6 with resistivity values ranged from 54.94-825.40Ωm with the thickness values also varied from 19.95-27.85m

VES 1 and 2 had five geoelectric strata and the first layer of the two VES corresponded to the topsoil with resistivity values of 34.02Ωm and 30.97Ωm respectively and its respective layer thickness were 1.79 and 2.52m. The second layer inferred to be Clay of resistivity 11.29Ωm and 13.16Ωm with thickness 4.47m and 10.62m respectively. The third substratum of VES 1 had very low resistivity of 5.31Ωm with thickness 12.09m. This was inferred to be Clay/peat while the third layer of VES2 also had resistivity value of 20.81Ωm with thickness 13.97m which corresponded to Silty Clay.

The fourth stratum of VES1 inferred to be silty clay with resistivity of 22.03Ωm and thickness of 22.03m but the fourth layer of VES2 inferred to be Sand with resistivity value of 192.18Ωm and with thickness

73.31m. The fifth substratum which was the last layer to both VES1and 2 was seen as a competent region due to high resistivity values of 56.22 and 147.30Ωm respectively. Hence, this inferred to be Sand and the depths cannot be determined because current terminates within the thin Zone.

BEARING CAPACITY FROM CPT RESULTS

The CPT data sets were interpreted by using a correlation table for cone resistance and depth by Kerisel(**1980**) table8. Beneath CPT 1 (figure 5) a simple three-layer sequence was observed. The first layer which extends to a depth of about 12m has very low cone resistance values that range between 2kgf/cm^2 to 5kgf/cm^2 and has been interpreted to constitute peat deposits. This layer is succeeded by a stratum with moderate strength to a depth of about 14.5m; the cone resistance values of this stratum range between 15kgf/cm^2 to 20kgf/cm^2 see table 8. The third layer has relatively high cone resistance values of between 75kgf/cm^2 to 170kgf/cm^2 and extends to the base of the probe at 16m where the penetrometer anchors yielded.

A similar trend is observed beneath the other CPT points. Beneath CPT 3 and 4 (figures 5 & 6), the subsurface material is constituted of peat / soft clays to a depth of 8m at CPT 2 to a depth of 9m and at CPT 1 to a depth of about 12m. These weak materials are succeeded by progressively stronger materials becoming predominantly sand from a depth of 12m downwards.

On the other-hand, CPT 5 showed a contrary result with peat to a depth of about 2m and becoming progressively sandy to the extent of the penetration test.

CORRELATION OF GEOELECTRIC SECTION & CPT

The geoelectric sections of VES 5 & 6 reveals depth to competent layer (SAND) to be between 19.95m to 27.85m. This result is not far from the one of CPT1 that shows peat/soft clay to the depth of about 12 – 14.5m

Likewise, VES 3 & 4 reveal Clay/peat from the surface to the depth of about 0.77m to 14.85m which agrees with CPT. Beneath these depths lie competent sand with great thickness.

As observed from all the two tests; geophysical and CPT, carried out on the site, the subsurface material comprises of sand, clay and peat. The sequence of these materials indicated a depositional environment of a flood plain / lagoon.

A high level of concordance can be seen in the results of the two tests conducted. Although, the Vertical Electrical Sounding was indirect method employed, its result was remarkably comparable to that of CPT.

Basically, all the tests showed that the study area was underlain by weak materials to a depth of about 12m, becoming progressively stronger with increase in depth thenceforth. The weak material is constituted predominantly of peat and soft clays which have moisture content. As characteristic of peat deposits, they have high compressibility, high void ratio and low bearing capacity, thus they are unsuitable as foundation materials.

The thickness of the peat deposits was quite much and as such the use of shallow foundation within the study area is precluded. Unfortunately, most structures around the study area have shallow foundation and this might have been responsible for the failure observed.

4. CONCLUSIONS:

However, under the peat deposits, the soil strength appreciates, being constituted of sandy deposits with good geotechnical properties. The resistivity values of these sand deposits range between 20.38Ωm to 825Ωm and is delineated to a depth range between 16 – 73m.

Also, the VES tables equally established that lower range of resistivity values of clay and peat existed with thickness between 0.77 – 14.58m and were succeeded by materials with higher resistivities, thereby splitting the horizon into two; a moderate strength material and a strong material horizon.

The strong materials having high resistivity values and delineated beneath a depth of 15m have been considered as good foundation medium capable of bearing load of structures beneath the site and also as the major aquifer unit under the study area. Furthermore, this depth precludes the use of shallow foundations and as such foundations within the study area shall be restricted to piles; particularly foundations for superstructures.

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