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EXPLORING THE LINKAGES BETWEEN GEOPHYSICAL AND GEOTECHNICAL PROSPECTION TO DETECT FOUNDATION FAILURE OF BUILDINGS IN A WETLAND AREA OF LAGOS, SOUTHWESTERN NIGERIA

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ABSTRACT

The geophysical and geotechnical methods were used to characterize the sub surface geologic units with a view to establishing the causes of foundation failure at Oyadiran Estate, Yaba, Lagos, Southwestern Nigeria. 2–D Electrical Resistivity Imaging, Vertical Electrical Sounding (VES) and Multichannel Analysis of Surface Wave (MASW) were acquired within the study area. Also, a Standard Penetration Testing (SPT) boring was acquired to constrain the geophysical methods. The results of 2–D resistivity and 1-D geoelectric sections delineated four to five geologic units. These correspond to topsoil, clay/peat, sandy clay, clayey sand and sand based on resistivity contrast ranging from 0.25 – 226 Ωm. The 2–D resistivity sections emphasized the lateral and vertical extents of the subsurface geological information. The MASW results revealed similar geologic units based on shear wave velocity discrimination except in a few cases which might be due to subsurface dip of the earth materials. An analysis of a typical geotechnical borehole has assisted to classify sand into loose, medium dense and dense based on SPT N-values and clay into very soft arising from cohesion (cu) value. This study has established that the clay materials with resistivity in the interval of 0.25 – 27 Ωm, Vs values 60 – 80 m/s^2 and Cu of 12 -15 kN/ m^{2}could be responsible for the foundation failure. Hence, the integration of 2–D Electrical Resistivity Imaging, VES and MASW complemented with a SPT boring has assisted to reduce this uncertainty by identifying the anomalous zones for detailed and cost effective geotechnical investigation.

1. INTRODUCTION

Failures or collapses of superstructures in Nigeria in the past three decades have assumed a very worrisome dimension. Many lives have been lost and huge properties and investments wasted. This failure, though a common phenomenon all over the world, is more rampant and devastating in the developing countries (Folagbade, 2001). Many cases of failure and collapse of structures have been reported in Nigeria. Between 1980 and 1999, there were about forty-two (42) cases of building collapse (Chinwokwu, 2000; Folagbade, 2001) and

fifty-four (54) cases occurred between January 2000 and June 2007 alone (Makinde, 2007) to mention a few. Attention is paid to every other area of the building development except the subsoil conditions on which the foundation is laid. Building collapse has also been observed to cut across the different categories – private, corporate or public. Cases of building collapse are not restricted by climatic conditions or level of urbanization as they also cut across cultural and ethnical barriers.

An engineering structure either undergoes progressive or sudden failure when a primary structural element fails, resulting in the failure of adjoining structural elements. Foundation problems are caused by a combination of soil conditions, the weather, inadequate foundation maintenance and geological features (Oyedele *et al.*, 2009). In many coastal areas of the world, including Lagos, the near surface soil is of expansive clay, which behaves differently than sandy soil (Fitterman and Deszez-Pan, 2001). Unfortunately, it is not easy to identify soil properties in transitional areas with enough certainty to satisfy this requirement. It is worthy of note that every geotechnical in-situ survey gives only discontinuous one-dimensional information in respect to the subsurface conditions (Oyedele *et al*., 2015). The use of non-destructive geophysical methods to guide geotechnical investigations has continued to gain rapid attention among earth scientists (Sirles, 2006). The application of engineering geophysics could provide either 2–D or 3–D subsurface images of the study area with low cost and time. Integration of geophysical techniques involving Multi-Electrode Resistivity (MER) testing, as well as Multichannel Analysis of Surface Waves (MASW) which is a seismic method of geophysical mapping have found good applications in recent times to determine sub-surface density variations with variations in shear wave velocity as rock stratigraphy change in the subsurface (Nettles *et al.,* 2005). This in lucid terms will characterize the intervening lithologies in terms of geology (Borcherdt, 1994).

The inability of the available point-specific geotechnical boring in the study area to give lateral extent of the subsurface has therefore necessitated the involvement of the geophysical methods as a compliment. Hence, in this study, VES, 2D-ER, MASW and a boring with SPT-N value were combined to characterize the subsurface conditions with a view to solving the incessant problems of foundation failures in the study area.

2. MATERIALS AND METHODS

2.1. Location and Geology of Study Area

The study area, Oyadiran Estate, Sabo, Yaba, Lagos, is in Wetland region of Lagos, Southwestern Nigeria which is bound to the west by the Republic of Benin, to the east and north by Ogun state and to the South by the Atlantic Ocean. The geology of Nigeria is predominantly of both basement complex and sedimentary environment (Kogbe, 1976). The general geological map of Nigeria is shown in Figure 1. The study falls in the sedimentary area. The sedimentary rocks cover about 6500 square kilometers of Nigeria (Jones and Hockey, 1964). The sedimentary environment is largely composed of sedimentary rocks and sometimes of various earth materials. Approximately fifty per cent of the surface area of Nigeria is covered by sedimentary rocks, which is usually composed of sands, sandstones, limestone, and clay (Kogbe, 1976). The stratigraphy of Cretaceous to Tertiary sedimentary sequence of the Eastern Dahomey Basin can be divided into: Abeokuta Group, Imo Group, Ilaro Formation, Benin Formation, Coastal plain sands and recent alluvium (Omatsola and Adegoke, 1981).

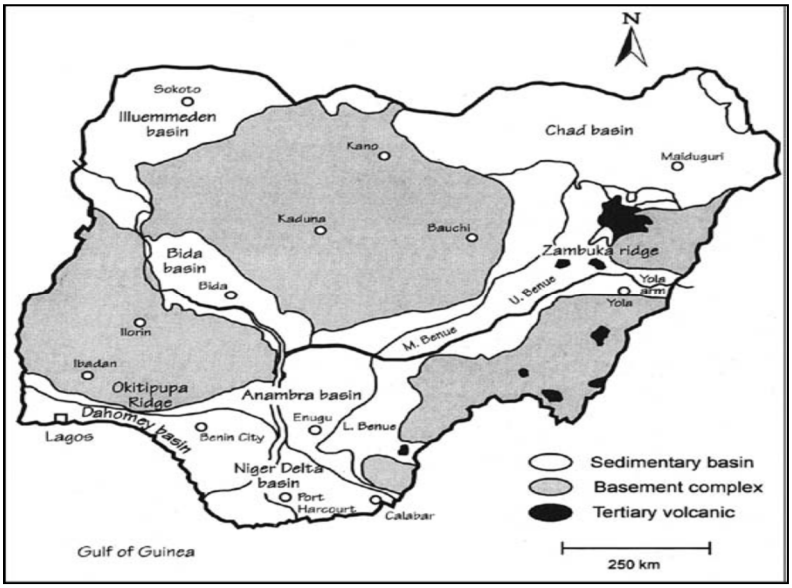

Figure 1: Geological Map of Nigeria (Jones and Hockey, 1964)

2.2. Geophysical Investigation

The 2D ERI measurement was carried out along three traverses (TR1, TR2 and TR3) with TR1 and TR3 oriented in NE – SW direction and TR 2 oriented perpendicularly to TR1 and TR3 in the NW – SE direction as shown in Figure 2. Using PASI 16GL resistivity meter model, the ERI sets of data were acquired using Wenner electrode array. The minimum and maximum inter electrode spacings were carried out along a spread of 130 m, 125 m and 52 m on TR1, TR2 and TR3. The 2D ERI survey was a reconnaissance to the proceeding VES field data acquisition and was carried out to show both the lateral and vertical distribution of resistivity structures within the study area. The 2D ERI data sets were processed for inversion with DiproWin Software to generate the pseudo sections and calculate the true resistivity distribution within the area. Anomalous resistivity points were identified across the sections and these were later occupied with the VES. Following the ERI measurement, sixteen (16) VES points were occupied across the three traverses with six VES points (V1 to V6) on TR1, five VES points (V7 to V11) on TR2 and five VES points (V12 to V16) on TR3 (Figure 2).

The VES points were selected to coincide with the suspected anomalous zones on the ERI sections. The sounding curves were processed with partial curve matching to quantitatively generate the first order geoelectric parameters. These were used as input parameters for inversion using WINRESIST iteration software. Spatial correlations of the resistivity, thickness and depth were used to generate the geoelectric sections along the traverses using AUTOCAD software.

MASW surveys were carried out on each traverse using the ABEM Terraloc Mark 6 seismograph. The geophones were arranged parallel to the profiles. A spread of 36 m, 120 m and 110 m were occupied on TR1, TR2 and TR3 respectively due to space availaibillity. The measured seismic data were processed using the SeiesImager Software to obtain the shear wave velocities. Table 1 shows range of velocities for common soil types used in the calibration of MASW results.

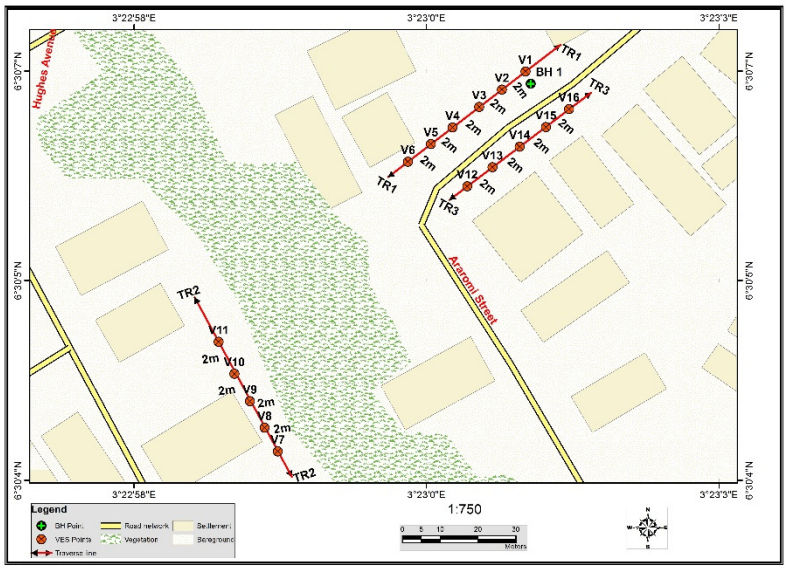

Figure 2: Base map of the study area

Table 1: Soil Type and S-wave velocities (Borcherdt, 1994)

NEHRP Site Classification	Average shear wave velocity (Vs)
Special Study may include sensitive clays, peat, highly organic clays and soft soil deposit more than 37m thick.	Less than 100 m/s
Soft soils (loose submerged fills and very soft (N<5 blow/300m) clays and silty clays< 37mm thick)	100 to 200 m/s
Stiff clays and sandy soils (e.g loose to very dense sands, silt loams, sandy clays and medium stiff to hards clays and silty clay (N>5 blows/300mm)	200 to 375 m/s
Gravelly soils and soft to firm rocks (e.g. soft igneous sedimentary rocks, sandstones, shales, gravels, and soils with >20% gravel	375 to 700 m/s
Firm and hard rocks	Greater than 700 m/s

2.3. Geotechnical Investigation

One boring with SPT was performed to an average depth of 30 m to reveal the ground truth soil profile of the subsurface earth materials. The undisturbed sample (clay) was taken to the laboratory for undrained triaxial test. The boring data were interpreted in terms of sample description (lithology), depth and NSPT values. Figure 3 shows the geotechnical borehole log generated from the boring samples to calibrate the MASW, 2D ERI and VES data.

DEPTH(M)	Sample Description	Symbol	NSPT Values							
0.00			0	10	20	30	40	50	60	70
1	Loose, Grey sand (fill)									
2	Very soft, Dark Brown Clay		0							
3										
4	Very soft, Dark Grey Peaty Clay									
5										
6			0							
7										
8										
9			0							
10										
11										
12										
13										
14			0							
15	Medium dense, Brown Clayey (medium) Sand			12						
16										
17				12						
18										
19				14						
20										
21										
22										
23	Dense, Light Grey (fine to medium) Sand						42			
24										
25							44			
26										
27								50		
28										
29										
30								50		

Figure 3: Boring with sample description and N-values

3. RESULTS AND DISCUSSION

2D Resistivity structure with superimposed geotechnical borehole log, Geoelectric Section and MASW along traverse 1 are presented in Figures 4a - 4c respectively. Figure 4a shows the 2D resistivity section along traverse 1. Along this traverse, at station positions 55, 57, 60, 65, 75, 80 and 82 m are VES 1, SPT, VES 2, VES 3, VES 4, VES 5, and VES 6 points respectively. The resistivity varies from 1 – 115 Ωm indicating peat/clay/clayey sand/sandy clay/sand. The low resistivity zone (clay/peat) is observed as pant-like structures to the left and right of the section with resistivity variation between 1.6 – 6.8 Ωm. This is the zone of interest in this study because it is inimical to hosting of any engineering structure. A relatively high resistivity zone in respect to the clay is observed to sandwich the clay layer and the resistivity is between 115 – 900 Ωm.

A geoelectric section constructed along traverse one is shown in Figure 4b. This section shows that four layers are demarcated under VES 1, 3, and 6 and five layers beneath VES 2, 4, and 5. The first layer is the Topsoil (54 – 155 Ωm, at 0 – 1 m depth) is believed to be made up of reclaimed soil. The second is sandy clay (61 – 76 Ωm at 1 to 3 m depth), clay (11 - 16 Ωm at 3 – 11 m) represents the third layer. The fourth layer is made clay/peat (2 – 5 Ωm from 11 m into the subsurface for VES 1 because the thickness of this lithologic column here could not be determined.). The fifth layer beneath VES 2 consists column of clayeysand (27 Ωm from 15 m into the subsurface for VES 2).

The 2D inverted shear wave velocity (Vs) model for the MASW survey along traverse 1 is shown in Figure 4c. A low shear wave velocity region is imaged as a pinch out structure at the shallow portion of the section characterized with velocity ranging from 40 – 120 m/s and is suggestive of clay/peat (Borcherdt, 1994). The intermediate Vs zone is seen as a constricted elongated structure throughout the section as characterized with Vs ranging from 120 – 240 m/s. This zone is made of soft soils (loose fills/soft clays based on Borcherdt, 1994 classification scheme). Since both the low and intermediate zones are characterized with relatively low Vs, these weak zones are not stable and incapable of support, thus not appropriate for hosting engineering structure.

An integration of the VES and 2D ERI results shows agreement as similar lithologic units both at the near-surface and at greater depth are demarcated. These results also agree well with the SPT boring test between VES 1 and VES 2 points along the traverse (Figure 4a). From the surface (0 - 1.8 m), the boring indicates loose sand which agrees with the topsoil nature from the VES and the clayey sand from the 2D ERI within the same subsurface depth interval as shown in Figures 5 (a - b). At 15 m depth, brown medium dense clayey sand was encountered. This result agrees well with the 2D ERI which defines same profile at the same depth interval. The boring result agrees with VES 2 and VES 6 only at the same depth interval. VES 4 and VES 5 indicate same lithology but at deeper depth (19 – 20 m) while VES 1 indicates clay/peat at 15 m depth. At 23 – 30 m, the boring indicates medium dense to dense sand. This agrees with both the 2D ERI and the VES except for minor variations in the VES results at the same depth interval. The MASW tomographic inversion distribution result from the shear wave velocity (Borcherdt, 1994) at traverse 1 is shown in Figure 4c which are earth materials of clays, peat, highly organic clays and soft soil deposits (Table 1) from 0 - 2 m depth. This is equivalent to the topsoil earth materials indicated by the 2D ERI, VES and the SPT at the same depth interval. At 3 - 5 m the tomography reveals that the subsurface is underlain by stiff clays and sandy sediment (Table 1). This agrees with the results from VES, 2D ERI and SPT except for a fairly large variation in the depth (Figure 4c). At 5 - 30 m depth, the subsurface is composed of gravelly soils with soft to firm rock such as soft sedimentary rocks, sandstones, shales, gravels, and soils (Borcherdt, 1994). This is equivalent to the sandy earth materials indicated by the 2D ERI, VES, and SPT and the result agrees only at deeper depths (20 – 30 m) with the 2D ERI, VES and SPT.

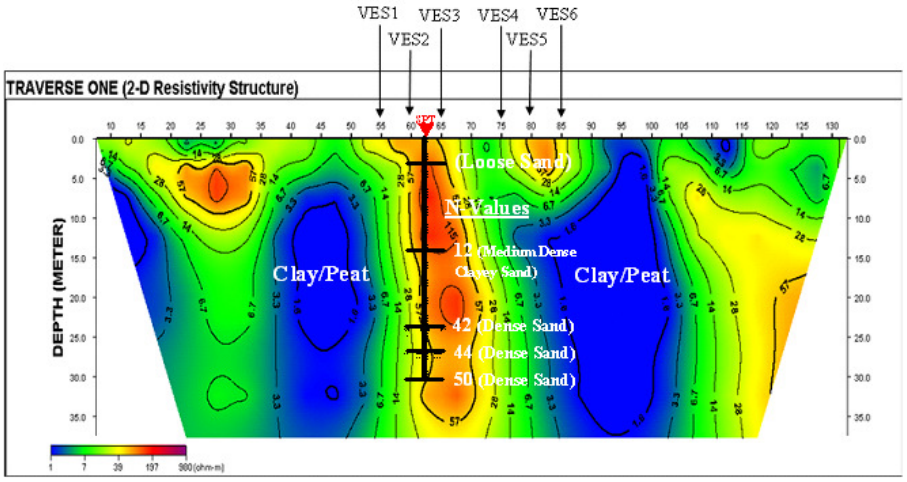

Figure 4a: 2D Inverse resistivity section of traverse-1 with SPT N-values and lithologic units emplaced at station 55.5 m

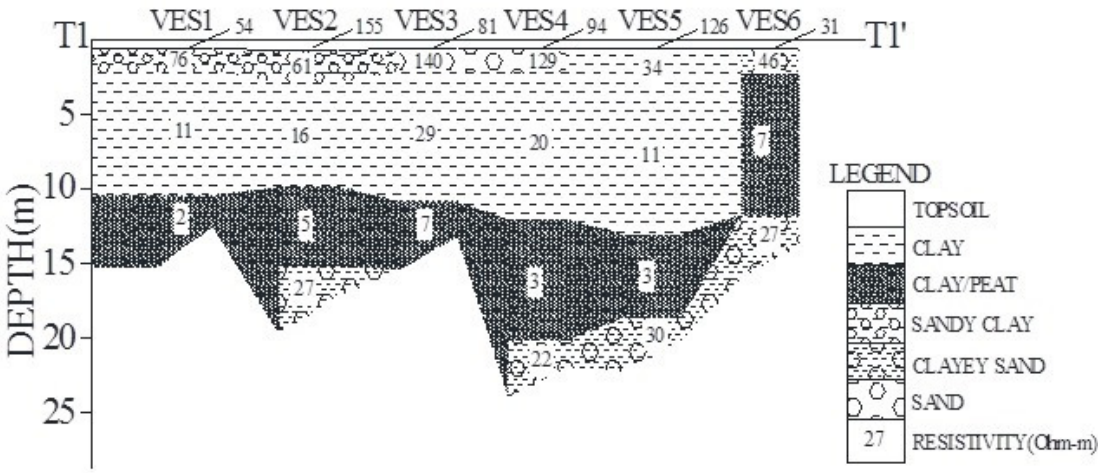

Figure 4b: Geoelectric section along traverse 1

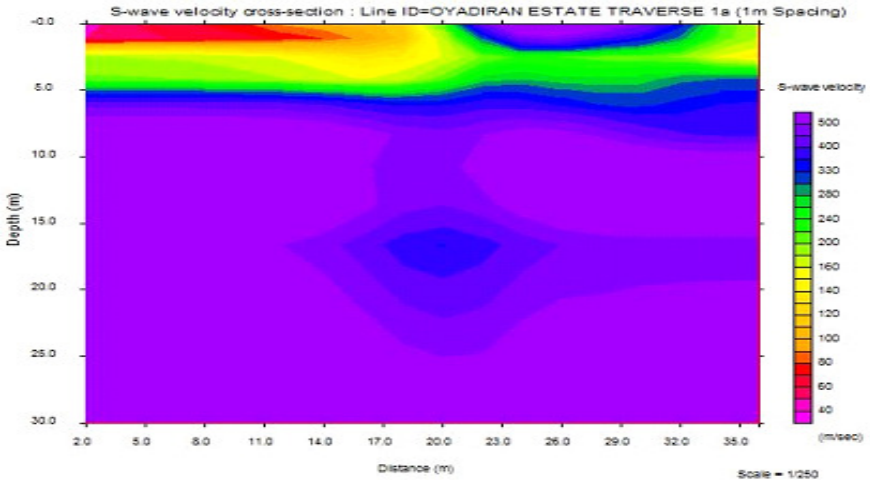

Figure 4c: 2D inverted tomograph for MASW along traverse 1

2D Resistivity Structure, Geoelectric Section and MASW along traverse 2 are presented in Figures 5a - 5c respectively. The 2D ERI shows that the lateral distance of survey is 52 m and the maximum depth of investigation is 14 m. The inverted section depicts that three zones are distinctively demarcated. These zones are grouped as low (blue), intermediate (greenish yellow), and high (red) on the bases of resistivity distribution in the section (Figure 5a). The observed resistivity values vary from 0.83 to 8 Ωm. The geomaterials that make up this section are topsoil, clayey sand/sandy clay, clay/peat and sand. The clay/peat layers which are noticed from 2 m of the section as pockets of clay and elongated wedge downward at lateral positions of 24-38 m, 42 - 46 m, and 6 -22 m respectively. It follows therefore that the clay/peat layers due to the low resistivity values, is the zone of interest in this study. It is a poor engineering material and being prone to instability even when unstressed, as identified as the possible cause of structural failure in the investigated area.

The geoelectric section T2 – T2' displays the spatial correlation of the inferred geoelectric layers along traverse 2 from VES 7 to VES 12 is shown in Figure 5b. The entire section shows a four layer model beneath all the VES points. Visual inspection indicates that the first layer, the topsoil (i.e., reclaimed soils) has resistivity that varies between 22 - 64 Ω-m. The rest of the section (i.e., the second, third and fourth) shows the presence of conductive geomaterials corresponding to clay/peat sediments. This geomaterial has resistivity less than 15 Ω-m.

The inverted 2D shear wave velocity model is shown in Figure 5c. This section depicts the variation of shear wave velocity (Vs) with depth. The highest velocity zones are clearly observed in the deepest portion of the inversion model. Interestingly, low velocity anomalies are observed near to the surface of the model. The Vs for this zone is between 65 – 252 m/s. This anomaly could be explained as soft soils (Borcherdt, 1994). The high Vs zone which is the deeper portion of the section corresponds to velocity ranges from 503 – 910 m/s. It represents sand sediments. The 1D VES result agrees with the 2D ERI up to a depth of 14 m (Figure 5a). Beyond this depth, the geosection reveals the presence of clay earth material. The MASW tomograph (Figure 5c) imaged 36 m maximum depth and covered a horizontal distance of 118 m. Three (3) velocity facies are delineated from the analysis of the shear wave velocity (Table 1). The near-surface up to 6 m depth is underlain by soft soils (which are symptomatic of loose submerged fills and very soft clays and silty clays). This result is well in consonance with the 2D ERI and the geosection denotes clay / peat in the same depth interval. At 6 to 25 m depth, the subsurface is characterized by gravelly soils and soft to firm rocks (Table 1). This result is not in agreement with 2D ERI (Figure 5a) and the geoelectric section (Figure 5b) which defines relatively soft soil (sandy clay /clays and / peat clay) at that depth interval with the 2D ERI being at a shallower depth (Figure 5a)

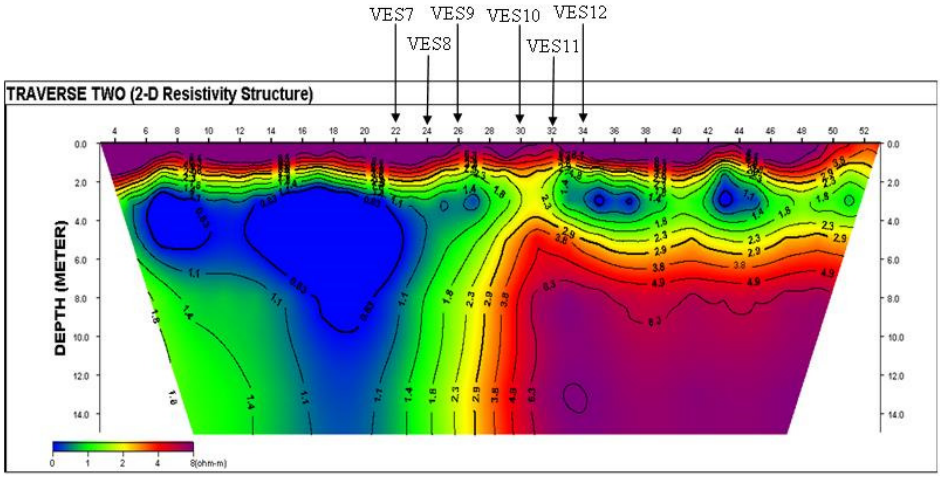

Figure 5a: 2D inverse resistivity section of traverse 2

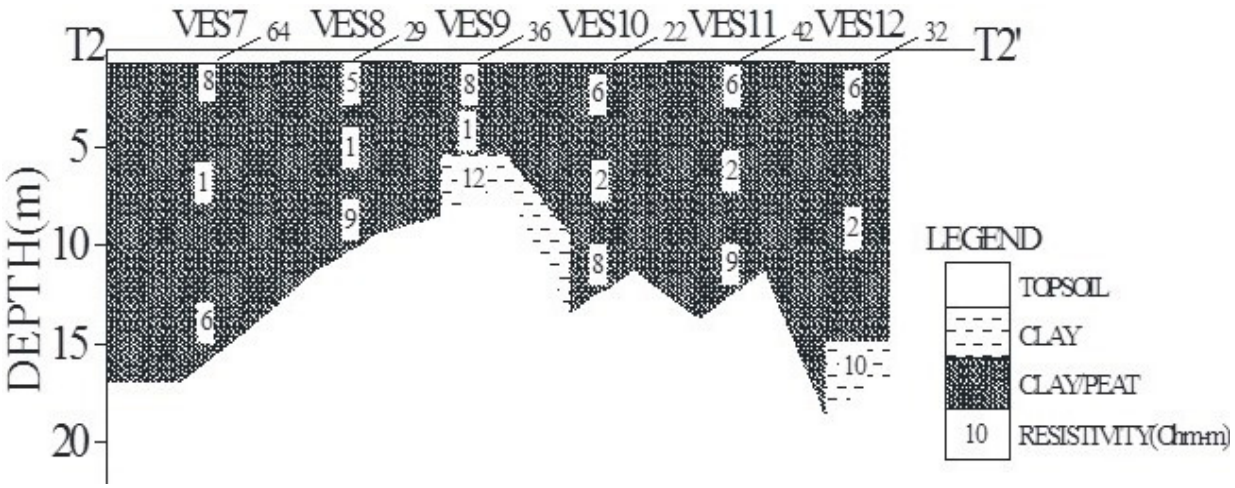

Figure 5b: Geoelectric section along traverse 2

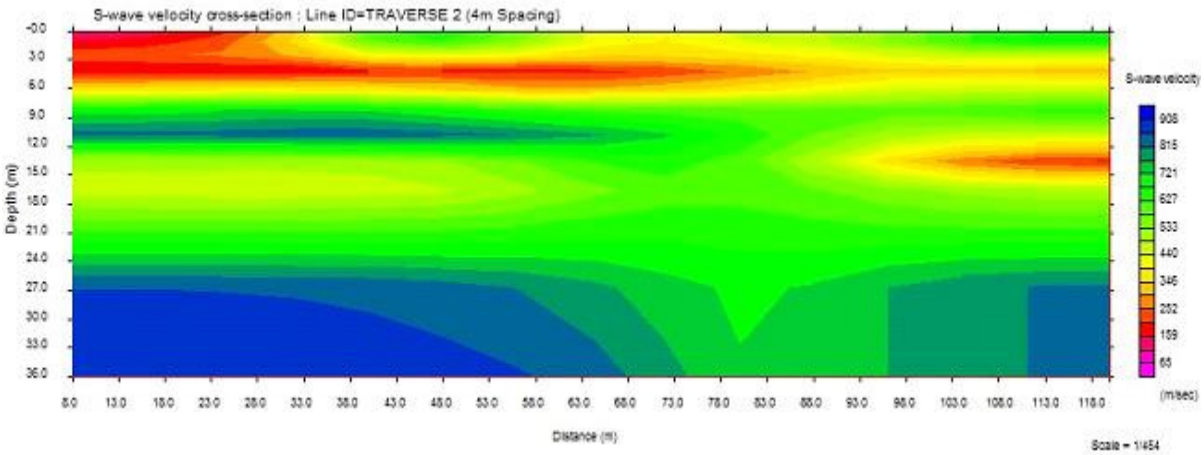

Figure 5c: 2D inverted for MASW along traverse 2

2D Resistivity Structure, Geoelectric Section and MASW along traverse 3 are presented in Figures 6a - 6c respectively. Figure 6a shows that resistivity value varies from 0.25 to 226 Ωm (Figure 6a). At 50, 55, 60 and 70 m along the traverse are the sounding points VES 13, 14, 15, and 16. Visual inspection of this section shows that three resistivity zones are distinctively demarcated which are diagnostic of near-homogeneous topsoil, clay / peat, sandy clay /clayey sand and sand (Figure 6a). The resistivity section shows what appears to be three zones of lower resistivity on left, central, and right sides of the section. This is seen to extend downward to a depth of 35 m in the section. This conductive zone is the zone of interest in this study, being unstable, the prevalence of the clay layer accounts for the failure of most buildings in the study area. The geoelectric section for the VES points on the traverse reveals the topsoil, underlain by clay/peat, clay and clayey sand (Figure 6b). At 5 to 20 m depth of the geosection, the lithology unit is symptomatic of clay/peat at VES 14 to 16 while at VES 13, it is clayey sand up to 15 m depth and clay / peat from 15 to 20 m. These results correlate with the 2D ERI with similarity in the subsurface composition along profile at the same depth interval.

The shear wave velocity model in Figure 6c reveals that 0 – 3 m of the subsurface corresponds to near surface underlain by earth materials that are symptomatic of gravelly soils and soft to firm rocks e.g. soft igneous sedimentary rocks, sandstones, shales and gravels (Table. 1). This interval matches the topsoil both in the 2D ERI and geoelectric section. Between 3 to 7 m (Figure 6c) along the profile length is a layer that is composed of soft soils to stiff clays and sandy soils (Table. 1). This result is in agreement with both the 2D ERI and the VES geosection in this interval shows clay / peat. At depth between 7 to 36 m (Figure 6c), the subsurface is underlain by earth materials that are indicative of an intercalation of stiff clays and sandy soils at depth intervals (7 – 12 m and 15 – 30 m) to gravelly soils and soft to firm rocks at deeper depth (12 – 15 m and 30 – 36 m) (Table. 1). The former result (i.e the stiff clays and sandy soils) fairly correlates with both the 2D ERI (Figure 6a) and the geosection (Figure 6b) at same depth interval while the latter results (i.e the gravelly soils and soft to firm rocks), being at the deeper portion of the section do not have a correlation with the 2D ERI and geosection since they do not give infomation at greater depth in comparison to MASW tomography.

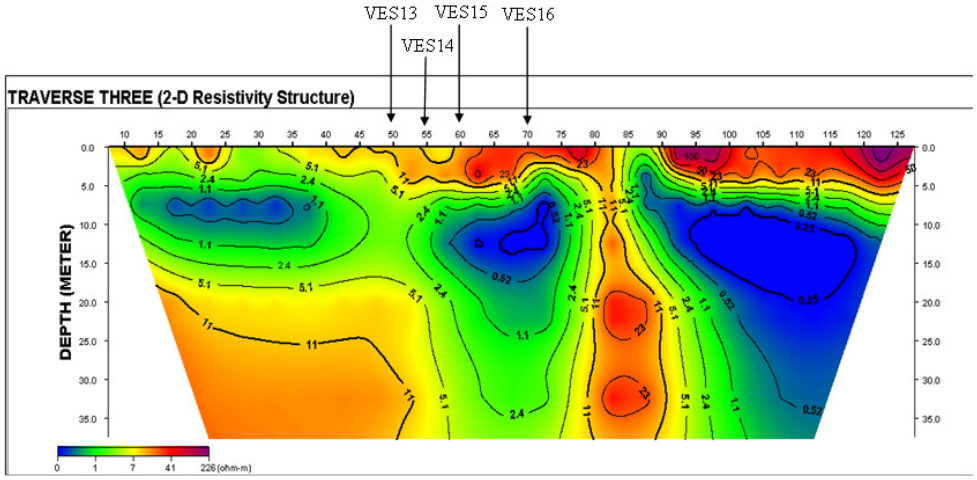

Figure 6a: 2D inverse resistivity section of traverse 3

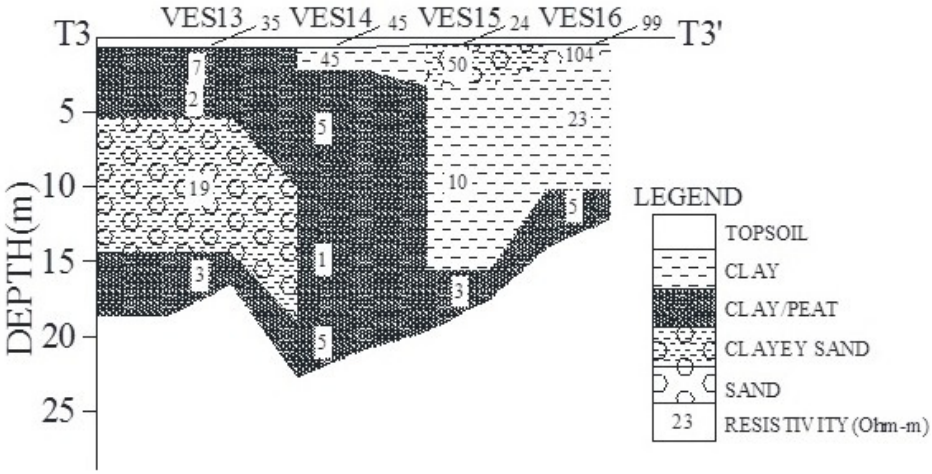

Figure 6b: Geoelectric section along traverse 3

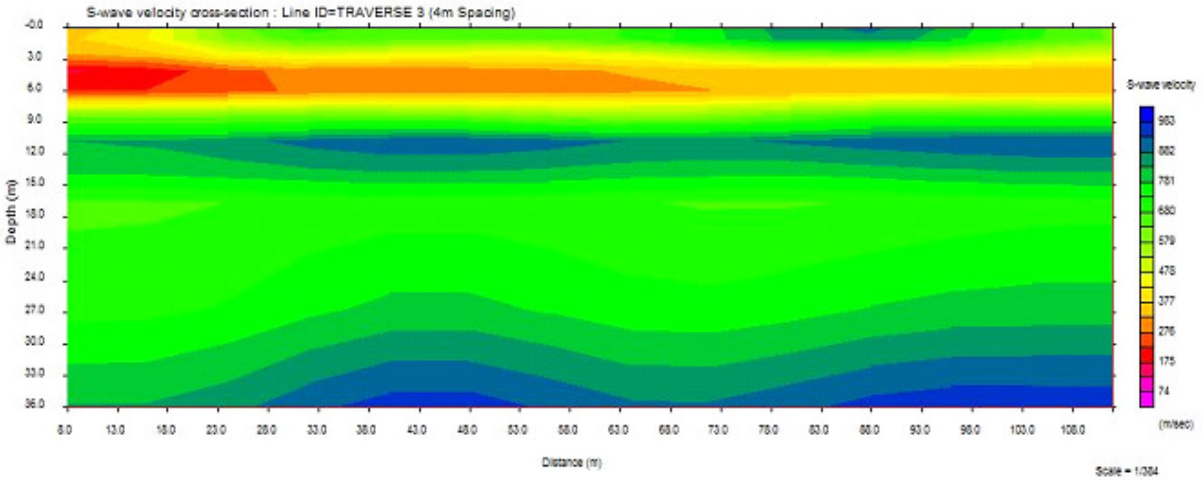

Figure 6c: MASW tomograph along traverse 3

4. CONCLUSION

Following the incessant collapse/failure of structures in Oyadiran Estate, in Lagos, Nigeria, this study investigated the surface conditions in the said area using integrated geophysical methods and constrained by standard penetration test from boring test. The combined approach made us to arrive at a more comprehensive interpretation for the results obtained. Results from 2D Electrical profiling, vertical electrical soundings, and seismic surface waves measurements yielded subsurface responses that we could link with the failure in structures prevalent in the area. The conductive clay/peat layer associated with low resistivity and low shear wave velocity has been identified to be the major cause of the failure. The implication of this is that any engineering structure whose foundation is sited within this column will definitely fail overtime because this unit of incompetent layer will quickly precipitate either uniformly or differentially depending on the moisture/water in the subsurface. Even a very shallow foundation at less than 5 m depth in the near homogeneous loose sandy topsoil in the area of study will share the same fate as earlier discussed since the sandy topsoil is underlain by the clay /peat / sandy clay layer. An imposed load on the thin sandy topsoil layer will be transmitted on the underlying clay layer which overtime will eventually settle to endanger the lives of the residents.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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