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*Full Length Research Paper*

# An application of 2D electrical resistivity tomography in geotechnical investigations of foundation defects: A case study

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**The high spate of differential settling and/or sudden collapse of buildings in Lagos has necessitated a holistic approach to foundation investigation prior to the erection of such structures as a panacea to environmental and engineering tragedy of our time, which we try to address in this work. In this paper, a 2D electrical resistivity tomography (ERT) and geotechnical investigation were carried out at Ogudu Estate in Lagos, Nigeria. The field geometry was made up of eight traverses; each measuring 315 m. 64 electrodes were deployed with inter-electrode spacing of 5 m, to cover the study area. Three cone penetrometer test (CPT) and a standard penetration test (SPT) were conducted to identify the depth to competent layer as a constraint for ERT survey. The CPT and SPT tests shows that the subsurface around the area is composed of materials of very low shear strength (< 5 kg/cm$^2$) interpreted as peat/clay at near surface to a depth of 8.2 m (being the maximum depth probed by the CPT test) and 25 m for the SPT. This agrees with the ERT result as the peat/clay was delineated to a depth of 25 m under the second half of most of the traverses which have high proximity to the SPT test hole. However, the inimical clay/peat layer was mapped to a deeper depth of 50 m under the first half of some of the traverses, alluding to heterogeneity of the subsurface layer in the study area. Generally, the overall depth to competent layer that could support a sizeable engineering structure is confined to the second half of the surveyed area north east (NE) portion as indicated in almost all the profiles at deeper depth mapped by ERT. Thus, the study shows that foundation investigation need be complemented with geophysical survey. By this way, where the engineering soil tests terminates geophysical survey could continue and could be a veritable tool to decipher deeper subsurface structures inimical to engineering construction.**

**Key words:** Foundation investigation, engineering structures, tomography, competent layer.

## INTRODUCTION

The need for shelter in the ever-congested metropolitan city of Lagos has led to the development of regions that under normal circumstances are not considered fit to erect structures. These regions include swamp forest, old river paths, flood zones, coastline, and other similar regions. Various reclamation exercises going on in Lagos have shown the urgent need for land in order to cope with shelter for the increasing population and their socio-economic infrastructures. However this drive had led many to develop regions that are either swampy or with unstable superficial soil formation that are unfit for erecting foundation of structures. This had resulted in differential settling of buildings and their eventual or sudden collapse. Thus, this has necessitated a holistic approach to foundation investigation prior to the erection of such structures or site investigation as a panacea to environmental and engineering tragedy of our time.

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**Figure 1.** Samples of affected building structure from the area.

Advances in technology have brought about innovations and development of geophysical methods to solve various problems encountered by mankind in his quest for better life. Electrical resistivity method is not left out in this move. The method had been applied to the evaluation of temperature of soil (Briggs, 1899) and water content (Edlefsen and Anderson, 1941), evaluation of soil salinity (Halvorson and Rhoades, 1976; Chang et al., 1983; Rhoades et al., 1989), groundwater and mining survey (Olorunfemi and Okhue, 1992), and geotechnical investigation and geological mapping (Olorunfemi and Meshida, 1987; Ayolabi et al., 2004). In addition, the 1D electrical method had been improved to a two dimensional imaging of the subsurface (Dahlin and Loke, 1998; Olayinka and Yaramanci, 2000; Chambers et al., 2002). More recently, D-C electrical resistivity methods had been used for environmental studies (Loke, 2000, 2004; Ayolabi et al., 2010), soil characterization for engineering purposes (Sudha et al., 2009), and mapping of growth fault (Saribudak, 2010).

This work, however, aims at integrating geophysical methods with geotechnical data to proffer solutions to the collapse of buildings in the studied area and the possible precautions to avoid this devastating incidence. Partial defects are noticeable on building and fence walls in the area (Figure 1). This is a deviation from the conventional engineering soil characterization methods that lack complete imaging of the subsurface. Geophysical data interpretation can image the subsurface to the depths of competent layer and evaluate the real distribution of geological earth material.

## The study area

The study location (Ogudu) is a major part of Lagos metropolis located between 542071 and 542365 Northing and 726587 and 726453 Easting (Figure 2). It is mainly accessible through Ogudu road. Geologically, it falls within the sedimentary basin of south western Nigeria popularly called Dahomey basin. This constitutes part of the system of West African precratonic (Marginal sag) basin developed during the commencement of rifting, associated with the opening of the Gulf of Guinea in the early Cretaceous to late Jurassic. The Dahomey basin is a very extensive sedimentary basin in the Gulf of Guinea. It extends from the south eastern Ghana through Togo and Benin Republic on the West side to the Okitipupa ridge/Benin Hinge line in the east side in the southern part of Nigeria. The basin consists of Cretaceous tertiary sedimentary sequence that thin out on the east and are partially cut off from the sediment of the Niger Delta basin by the Okitipupa ridge. In general, rocky outcrops are poor due to the thick vegetation and soil cover. The knowledge of the geology of this basin had been improved through the availability of boreholes and recent road cuts. Major lithological sequences associated with the basin are: Abeokuta formations (Ise, Afowo, and Araromi formations), Ewekoro, Akinbo, Oshoshun, Ilaro and Benin formations, and coastal plain sand. Geologically, the study area falls within the loose sediment ranging from silt, clay, and fine to coarse grained sand, called coastal plain sand. The exposed surface consists of poorly sorted sands with lenses of clays. The sands are in part cross bedded and show transitional to continental characteristics (Jones and Hockey, 1964; Omatshola and Adegoke, 1981; Agagu, 1985; Enu, 1990; Nton, 2001).

## METHODOLOGY

The research employed both geophysical and geotechnical surveying methods in delineating regions that are fit for erecting foundation of structures. There was a reconnaissance survey before the area was mapped out to determine the number of profiles and where geotechnical survey would be carried out. In addition, borehole information from the standard penetration test (SPT) was used to constrain the interpretation of resistivity data.

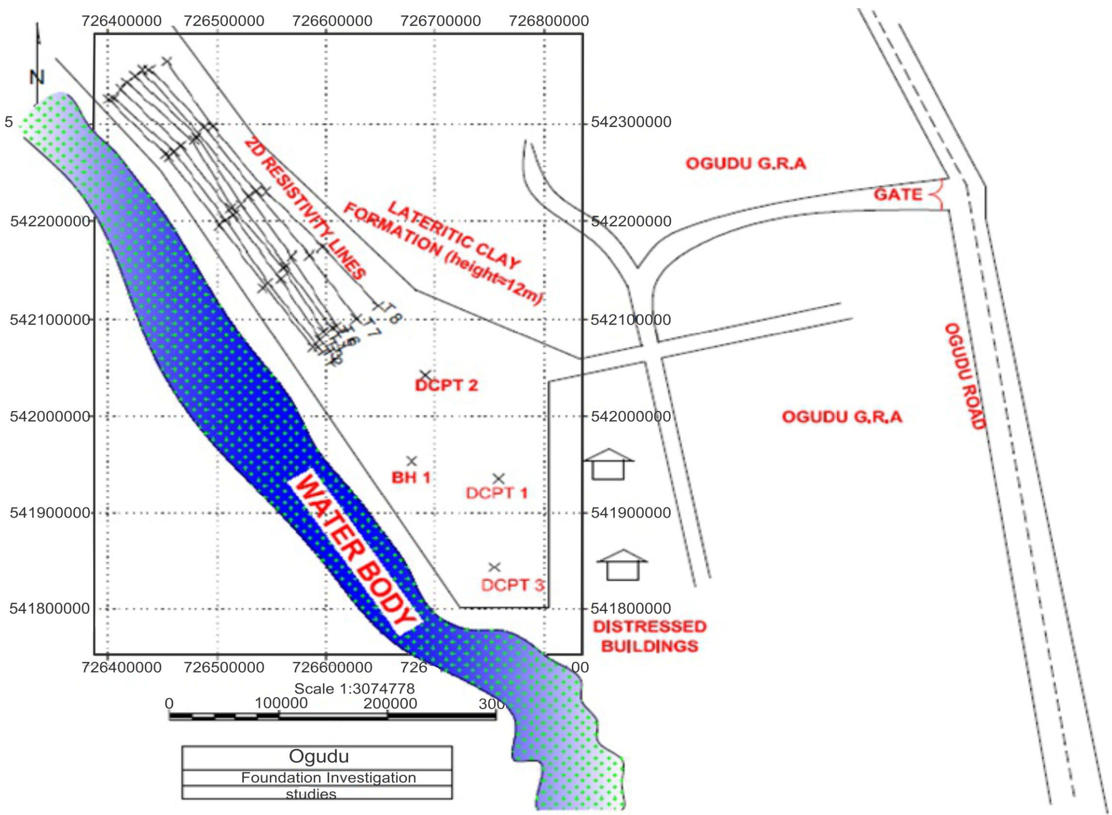


**Figure 2.** Location map of the study area, showing the locations of electrical resistivity tomography (ERT) profiles, borehole (BH1) and dynamic cone penetration test (DCPT) at the study Site in Ogudu.

The survey area is difficult to access due to swamp, peat, and thick vegetation. This necessitated cutting through the vegetation to create path for the traverses established.

### Geophysical survey

Electrical resistivity data were acquired using ABEM SAS1000 terrameter along eight traverses with Gradient and Wenner configurations using a multi electrode system (Figure 2). The instrument is capable of measuring apparent resistivity with induced polarization (IP) or self potential (SP) at the same time, though with increase data acquisition time. In the present work, we measured IP with the resistivity owing to the usefulness of IP in lithology identification (Ayolabi et al., 2010). The initial electrode spacing of 5 m for 64 electrode systems was utilized which sums the total length covered to be 315 m. The traverse was acquired in the North west (NW) direction.

Both resistivity and IP inverted models were computed with Earth imager software from AGI Incorporation, Austin, United State. Smoothness constrain least square inversion technique (Dey and Morrison, 1979; DeGroot-Hedlin and Constable, 1990; Loke, 1994) employed divided subsurface into small rectangular cells where its positions and sizes were fixed by forward modelling. The resistivities of the blocks were adjusted and iterated until the calculated and field apparent resistivities agreed to barest minimum differences (Loke et al., 2003; Loke, 2004). The differences were expressed in percentage as root-mean-square error (RMS error), which ranges from 0.53 to 5.47 for the present work. The inverted sections depict subsurface resistivity values against electrode positions were presented in Figure 3 for the electrical resistivity tomography (ERT and the IP models.

### Geotechnical survey

Generally, methods of observing the soils below the surface (to obtain information about the soil conditions), obtaining samples, and determining physical properties of the soils and rocks below the surface, include test pits, trenching (particularly for locating faults and slide planes), boring, and in situ tests such as cone penetration tests (CPT) or SPT. A SPT is an *in-situ* dynamic penetration test designed to provide information on the properties of soil, as a measure of resistance of soil to penetration (Sudha et al., 2009) while in the process of collecting a disturbed soil sample for grain-size analysis and soil classification. A CPT is performed using an instrumented probe with a conical tip, pushed into the soil hydraulically at a constant rate. A basic CPT instrument reports tip resistance and shear resistance along the cylindrical barrel. CPT data has been correlated to soil properties. CPT allows continuous recording of soil changes with depth, whereas SPT only records major changes at discrete steps of 150 mm (6 in); however, SPT allows soil sampling for laboratory testing. For the task at hand, the geotechnical surveys employed includes standard and cone penetrometer tests. Percussion drilling sampler used has a thick walled sample tube with an outside diameter of 50 mm and an inside diameter of 35 mm, and a length of around 650 mm. This was driven into the ground at the bottom of a borehole by blows from a slide hammer with a weight of 63.5 kg (140 lb) falling through a distance of 760 mm (30 in). The sample tube was driven

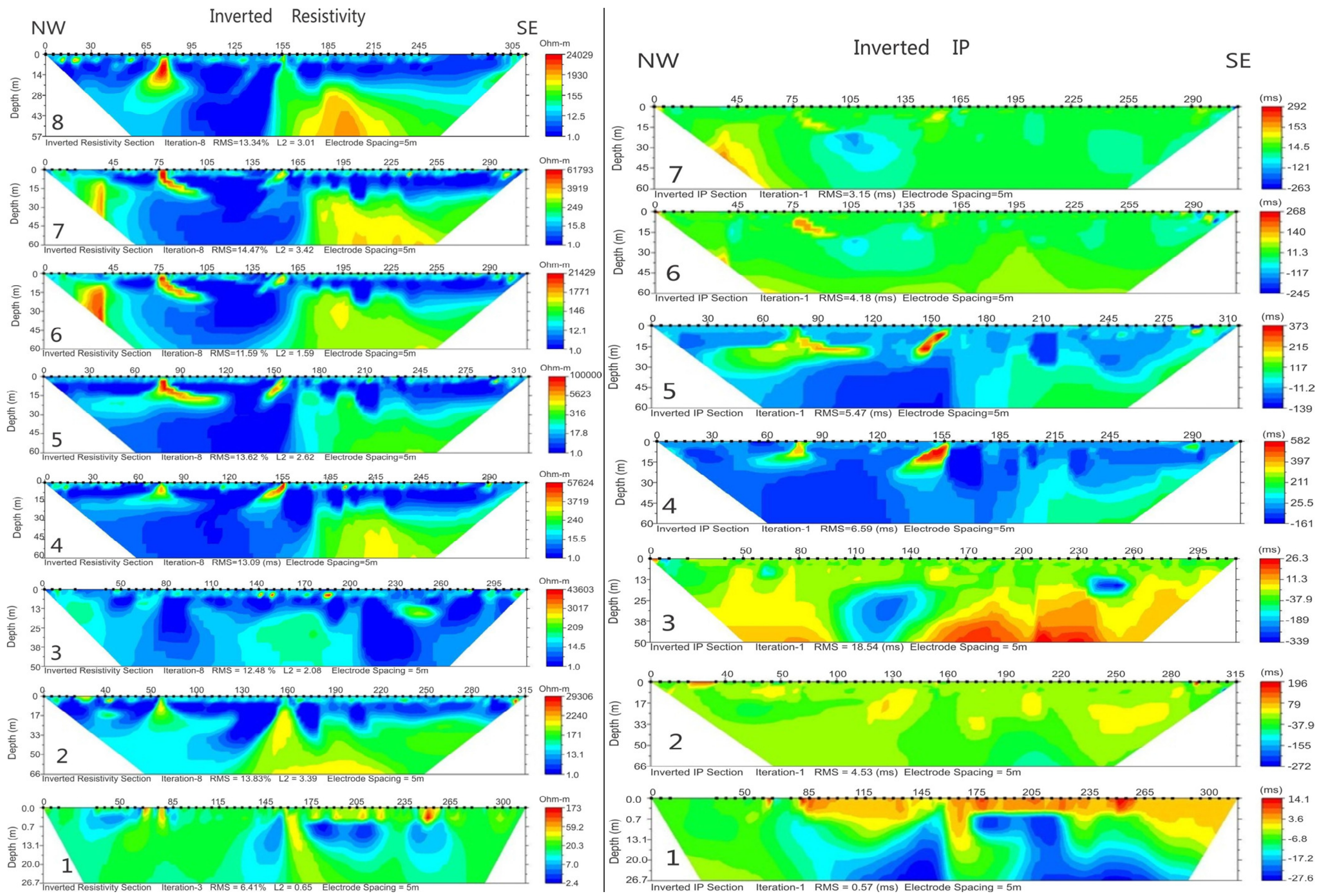


**Figure 3.** Stacked inverted models for the a) ERT and b) IP. The inverted models were stacked to reflect the direction and order of profiles from 8 to 1.

150 mm into the ground and then the number of blows needed for the tube to penetrate each 150 mm (6 in) up to a depth of 450 mm (18 in) was recorded. The sum of the number of blows required for the second and third 6 inch of penetration is termed the "standard penetration resistance" or the "N-value". The blow count provides an indication of the density of the ground, and it is used in many empirical geotechnical engineering formulae. The result was analysed based on the *in-situ* result as regards texture and particle sizes. The numbers of blow and relative depth of the drilled material were also measured and recorded

For the CPT, the cone tip was driven into the soil manually. A rod of 1 m is placed into the cone penetrometer and driven into the soil, the pressure is noted. At the cone head the cone resistance ($q_c$) was in megapascal (MPa), which expresses the resistance of the sediments to penetration. Along the cone the sleeve friction ($f_s$) was also recorded in MPa which indicates the adhesive strength of the material. Another rod was screwed to the driven rod and driven into the subsurface. This was continued until the cone penetrometer could not withstand to drive additional rod further into the subsurface soil. This is due to the inability of the surface to withstand the reaction of the driven rods. The cone reading (kg/cm$^2$) was plotted against the depth penetrated. The amplitude of the curve is a function of the resistance of the material to the penetration of the curve. This is indicative of its ability to withstand load. The point used for the SPT and the CPT during the survey were about 50 to 200 m away from the 2D electrical traverses due to difficulty in moving the heavy percussion and penetrometer instrument closer to the traverse.

## RESULTS AND DISCUSSION

### Electrical resistivity tomography result

The 2D electrical resistivity section along Tranverse 1 (Figure 4) is reflective of subsurface resistivity within the study area. The topsoil range from a depth of 0 to 6.7 m and compose of varying resistivity materials with resistivity value range of 2.4 to 173 Ωm suspected to be decomposed organic materials, vegetable remains, and pockets of exotic sand filling materials. The second geoelectric layer extend from a depth of 6.7 to about 26.7 m with resistivity range of 2.4 to 18 Ωm which is predominantly clay and peat materials. This layer is unfavourable for foundation of engineering structure along this traverse. The first half portion is made of silty sandy clay having low resistivity (20 to 50 Ωm range), possibly derived from the twin effects of silt and clay

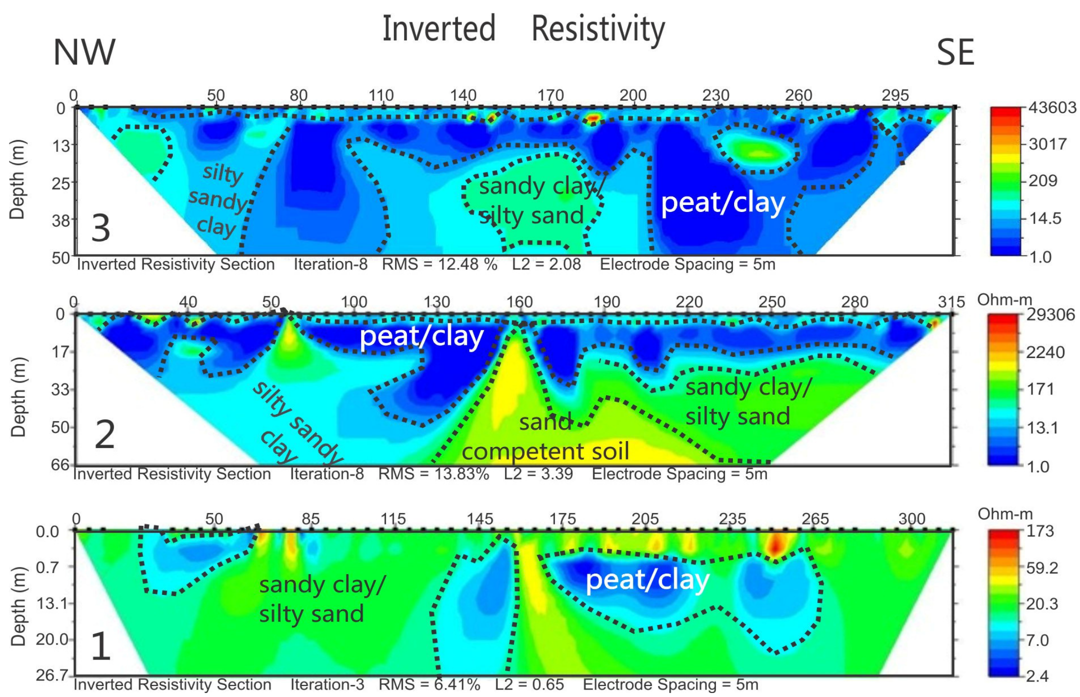


**Figure 4.** The raw and modeled resistivity section along the ERT for Profiles 1-3.

components and water saturation. This was noticed through all the inverted sections from all the profiles, the same was observed on the borehole log (Figure 8).

In the 2D resistivity section along Traverse 2 (Figure 4), the topsoil ranges from a depth of 0 to 8 m beneath the surface and compose of a varying resistivity materials (1.0 to 100 Ωm) suspected to be decomposed organic materials, vegetable remains, and sand filling materials. The second geoelectric layer extends from a depth of 8 to about 50 m with resistivity range from 1.0 to 13.1 Ωm predominantly made up of peat/clay material. The depth range of this material between lateral distances of 0 to 75 m is about 10 to 25 m, between 80 to 150 m is about 17 to 50 m, and between 165 to 315 m is about 20 to 35 m. This shows that the peat /clay material along this traverse have varying thickness and depth. This layer is inimical to the foundation of engineering structure along this traverse. The third geoelectric layer is compose of silty sandy clay having resistivity range of 14 to 90 Ωm with thickness ranging from about 4 to 50 m at a depth of 10 to 66 m. This is well saturated with water which can aid the easy flow of peat/clay materials overlying it. The fourth geoelectric layer is composed of silty sand/sandy clay and exists from the central portion to the south east (SE) axis of the survey (that is, lateral distance of 140 to 315 m). The resistivity value ranges from about 90 to 180 Ωm. This was underlain by high resistivity material, possibly sand and represents the competent layer for the foundation of engineering structure along this traverse. It exists within the depth range average of 35 to 66 m towards the SE axis of the survey line, which could be a major hydrogeologic unit of very good quality water within the study area.

The 2D resistivity section along Traverse 3 (Figure 4) shows that the topsoil ranges from a depth range of 0 to 6.5 m and compose of material with varying resistivity (1.0 to 800 Ωm) inferred to be composed of decomposed organic materials, vegetable remains, sand filling materials etc. The second geoelectric layer, extends from a depth of 6.5 to about 50 m with resistivity range from 1.0 to 14.5 Ωm and compose predominantly of clay/peat material. The depth range of this material between lateral distances of 35 to 110 m is 19.5 to 50 m, 110 to 205 m is 13 to 19.5 m, and 205 to 315 m is 25 to 50 m. The peat/clay material is sinusoidal in nature along this traverse and it has varying thicknesses and depths. This layer is inimical to foundation of engineering structure along this traverse. The third geoelectric layer is composed of silty sandy clay with resistivity range of 14.5 to 90 Ωm and thickness ranging from 2 to 30.5 m over a depth range of 6.5 to 50 m. This layer is equally saturated with water that may aid the easy flow of the peat/clay material overlying it. The fourth geoelectric layer is composed of silty sand/sandy clay and exists within the lateral distance of 140 to 190 m. The resistivity value is about 90 to 190 Ωm and which cannot support foundation of engineering structure along this traverse. It exists within the depth range of 19 to 48 m. Note high chargeability value of 113 mV/V over this layer indicating clay derived material.

In the fourth traverse (Figure 5), the topsoil depth range from 0.0 to 7.5 m beneath the surface and composes of

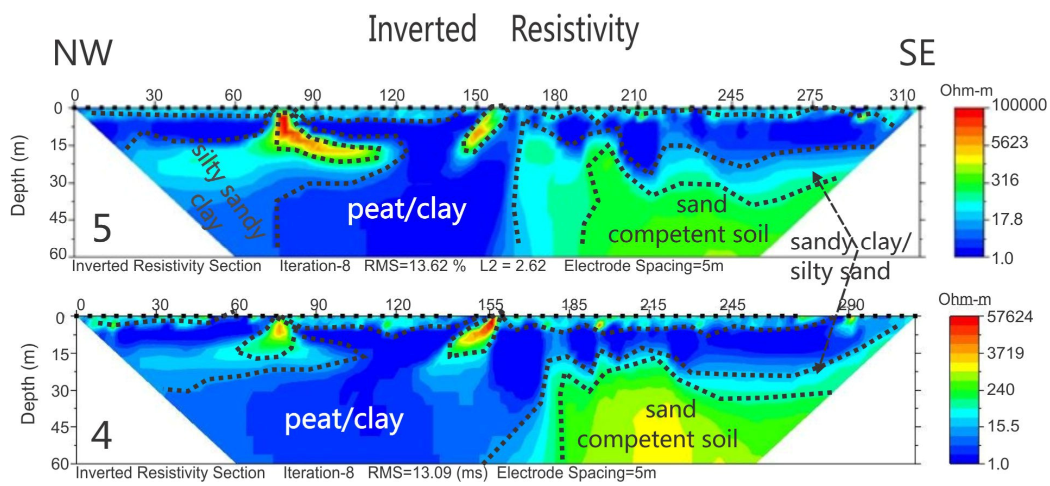


**Figure 5.** The raw and modeled resistivity section along the ERT for Profiles 4 and 5.

material with varying resistivity (1.0 to 1700 Ωm) suspected to be decomposed organic materials, vegetable remains, sand filling. The second geoelectric layer extend from a depth range of 7.5 to about 60 m with resistivity range from 1.0 to 15.5 Ωm and compose predominantly of peat/clay material. The depth range of this material within the lateral distance of 0 to 177 m is 22.5 to 60 m, and from 177 to 300 m lateral distance is 7.5 to 22.5 m. This shows that the thickness and depth of peat/clay varies like a wave along the traverse. This layer is inimical to the foundation of engineering structure along this traverse due to its poor shear strength. The third geoelectric layer is composed of silty sand/sandy clay from the central portion to the SE axis of the survey (that is, lateral distance of 180 to 315 m). The resistivity values range between 90 to 190 Ωm. Under this is a high resistive layer (200 to 1600 Ωm). This is interpreted as a competent sand layer for the foundation of engineering structure along this traverse. It exists within the depth range of 32.0 and 60 m towards the SE axis of the survey line and represents the major hydrogeologic unit of very good quality water within the study area.

The 2D resistivity section along Traverse 5 (Figure 5) produced the topsoil that ranges from the surface to a depth of 7.0m beneath the surface and compose of varying resistivity materials (1.0 to 35 Ωm) suspected to be decomposed organic materials and vegetable remains. The second geoelectric layer extend from a depth of 7 to about 60 m with resistivity value range of 1.0 to 17.8 Ωm and composed predominantly of peat/clay material. The depth range of this material between lateral distances of 0 to 165 m is 15 to 60 m and from 165 to 315 m is 9 to 27 m. This illustrates that the peat/clay material along this traverse has varying thickness and depth. This layer is inimical to the foundation of engineering structures along this traverse. The third geoelectric layer is composed of silty sandy clay materials with resistivity range of 17.8 to 90 Ωm and thickness ranging from 3.5 to 52.5 m at a depth of 15 to 60 m, found at the first half of the profile. This layer is the same water saturated layer as explained previously. The fourth geoelectric layer is compose of silty sand/sandy clay (90 to 180 Ωm), followed by sand at lateral position of 180 to 315 m. The resistivity value range from about 200 to 600 Ωm and represent the competent layer for the foundation of engineering structure along this traverse. It exists within the depth range of 35 to 60 m towards the SE axis of the survey and represents the major hydrogeologic unit of the study area.

The 2D resistivity section along Traverses 6, 7, and 8 (Figure 6) show similar lithology and structural disposition as those of Traverses 1 to 5 and confirmed that the depth to competent layer is shallow in the SE region (approximately 20 to 30 m) while it is deeper in the NE and central portion of the survey area. Major hydrogeologic unit of good quality fresh water was confined to the SE portion of the survey area at a depth of 32 to 60 m.

## Geotechnical analysis

### *Cone penetrometer test*

The graphs of the cone penetrometer reading are presented as penetration rate against depth in Figure 7. The depth penetrated by the penetrometer test is about 8.2 m. The readings show significantly low cone resistance of about 2 $kg/cm^2$ which indicates peat material. The linear nature of the graph shows constant penetration as the subsurface materials offer no resistance to the driven cone. The result on the CPT test indicates that the depth range of 8m penetrated is unfit for erecting the foundation of most structures due to its poor shear strength. This was replicated in all the CPT

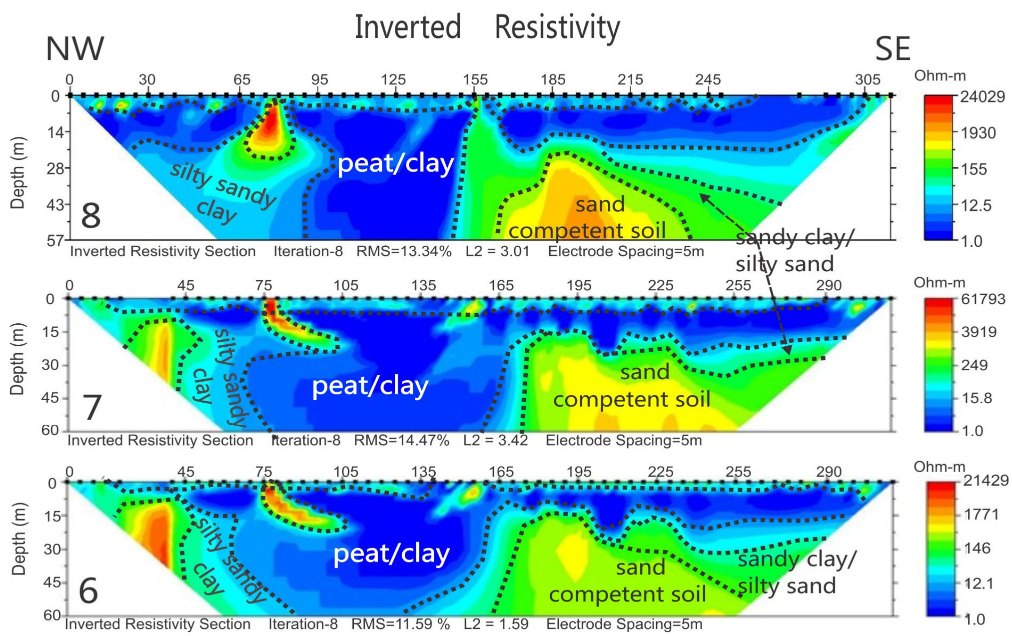


**Figure 6.** The raw and modeled resistivity section along the Electrical Resistivity Tomography (ERT) for Profile 7.

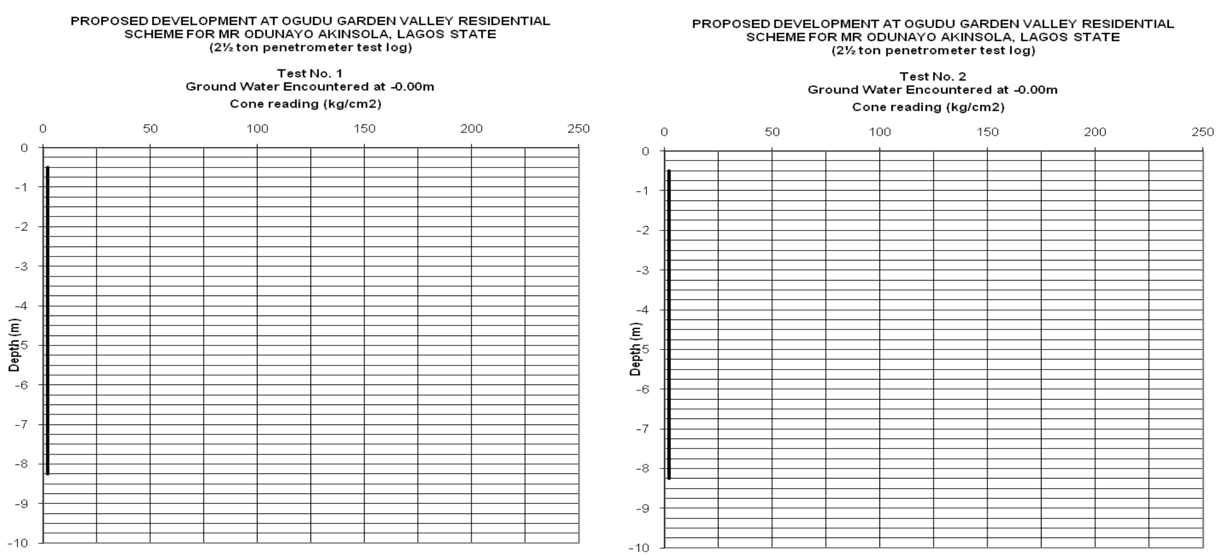


**Figure 7.** Typical CPT curve for the study area.

conducted in the area.

## Standard penetration test

A summary of the borehole log derived from the SPT is represented in Figure 8. During the percussion drilling exercise peat material was encountered within the depth of 0 to 25.5 m (Figure 8). This material is dark to brownish dark and soft in texture. This region is attributed with poor geotechnical properties, low shear strength and high compressibility potential. This region is not suggested for erecting foundation of most structures, Figure 8.

Below this material is silty to sandy clay material encountered at a depth range of 25.5 to 27 m. The material present at this depth is associated with moderate to good geotechnical properties. This region has

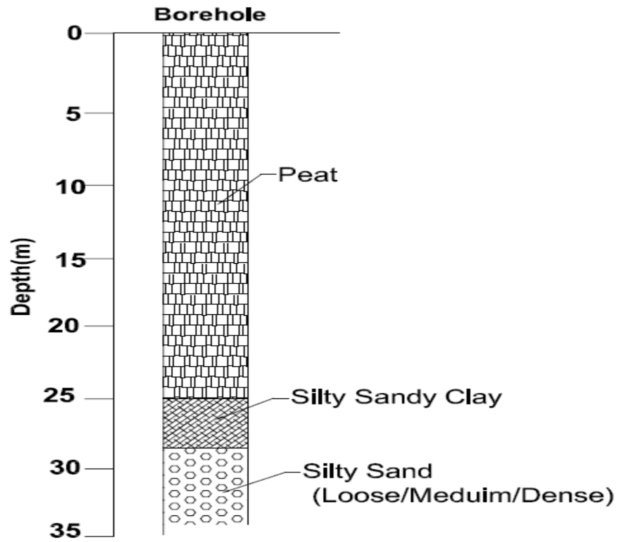


**Figure 8.** Sketch of strata derived from SPT borehole log.

**Table 1.** Lithological classifications based on ERT, SPT log, and CPT test in the area.

| Depth (m) | ERT | SPT | CPT |
|---|---|---|---|
| 0.0 – 5.0 | Decomposed organic materials, vegetable remains, and exotic materials | Peat (dark to brownish dark and soft in texture) | Peat/ clay (2 kg/cm$^2$) |
| 5.0 – 10.0 | Clay/peat /sandy clay/clayey sand (13 Ωm - 9 Ωm) | | |
| 10.0 – 15.0 | | | |
| 15.0 – 20.0 | | | |
| 20.0 – 25.0 | | | |
| 25.0 – 30.0 | Silty sand (90 Ωm – 19 Ωm) | Silty sandy clay | |
| > 30 | Sand (hydrogeological layer) (above 200 Ωm) | Silty sand (loose/medium/dense) | |

Note: For the ERT classification, no sharp boundary exists between the lithologies as they were extremely interwoven. It should also be noted that only SE portion of the ERT, which has high proxy to the SPT borehole were taken into consideration.

moderate to high shear strength and low compressibility potential. This region might be fit for sizable structures.

At the depth ranges of 27 to 30 m silty sand was encountered but with varying texture. The texture varies from loose, medium and dense silty sand and compact (derived from the number of blows). The material at this depth is associated with good geotechnical properties, high shear strength and low compressibility potential. This depth range is deemed fit to erect the foundation of most structures, but the thickness of the overburden to be removed may be costly.

## Correlation of 2D resistivity section with CPT and SPT

Table 1 represents the juxtaposition of the results from all surveys for better correlation of the results. The 2D resistivity tomography had revealed the varying depth to soil materials along each traverse. The CPT has indicated materials with low shear strength within the depth range of 0 to 8.2 m identified to be composed of peat. The SPT has also revealed this depth range to be composed of peat while the 2D resistivity section has shown material with low resistivity value (1.0 to 14.1 Ωm) prevalent to be peat/clay material.

The SPT revealed that the subsurface is composed of peat within the depth range of 0 to 25 m while the 2D resistivity section indicates this depth to be composed of low resistivity value material indicating peat. The presence of sandy clay material is revealed within the depth range of 25 to 27 m on the SPT and the 2D resistivity section has indicated this material to be with resistivity range of 14.1 to 90 Ωm. Sand material is

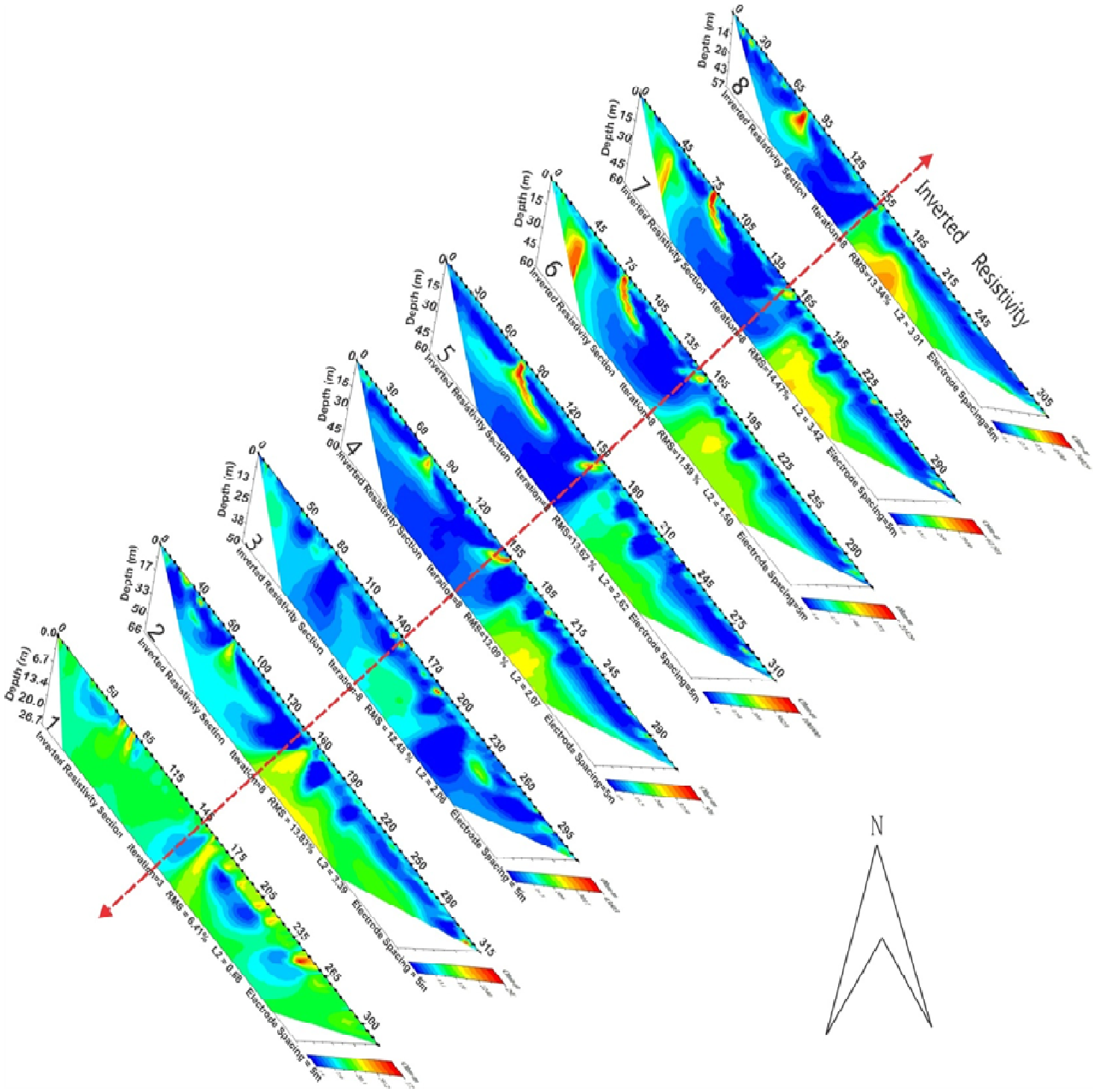

**Figure 9.** Stacked inverted ERT model showing lithological zoning of competent layer in SE portion of the area.

identified at 27 to 30 m on the SPT and represented by relatively high resistivity value range of 120 to 1700 Ωm on the 2D resistivity section.

The result of the borehole data at the SE portion of the study area correlates well with the second half of 2D resistivity tomography sections towards the SE portion of the study area. Stacked inversion sections of the eight ERT profiles well depict subsurface lithological zoning resulting in competent sandy layer being confined to the SE as shown in Figure 9. However, in addition to this, the 2D resistivity tomography has shown that the peat/clay material is much thicker within the central portion (30 to 60 m) of which there was no SPT or CPT information.

This clearly shows the need for the integration of resistivity tomography into various engineering site investigation for proper evaluation of soil integrity.

## Conclusion

Geophysical and geotechnical investigations have been carried out at Ogudu, Lagos State, South-west of Nigeria. Eight 2D resistivity traverses, three CPT, and a SPT were carried out in order to identify the depth to competent layer for foundation of engineering structures a priori to differential settlement of structures in this environ. Result of the geophysical survey indicates that the topsoil is within the depth range of 0 to 8 m and it is reflective of varying resistivity which indicates materials suspected to be decomposed organic and vegetal remains, and exotic materials used in sand filling of the area. The second geoeletric layer is composed of peat/clay material within the depth range of 7 to 66 m and resistivity range of 1.0 to 14.1 Ωm. The peat/clay material is with varying thicknesses and poor geotechnical properties which make it inimical to the foundation of engineering structures. The third geoelectric layer is composed of silty sandy clay having thickness range of 3 to 52.5 m and resistivity value range of 12 to 90 Ωm. The fourth geoelectric layer is composed of sandy clay/ silty sand material within the depth range of 15 to 66 m (in the NW and 30 to 42 m on the NE portion) and resistivity range of 90 to 180 Ωm. Sand material (> 200 Ωm) is prevalent towards the SE of the study area which represents the competent layer for the foundation of engineering structures and the hydrogeologic unit with very good quality water in the study area. The CPT probed an average depth of 8.2 m and has identified material of very low shear strength (≤ 5 kg/cm$^2$) associated with peat material. The SPT has indicated that a depth range of 25.5 m is composed of peat; 25.5 to 27 m is composed of silty/sandy clay while silty sand with varying texture can be sourced beneath the depth of 27 m. The result of the 2D electrical resistivity has been correlated well with that of the geotechnical investigations. The 2D resistivity survey has provided valuable information on the lateral and vertical variation of the layer competent for erecting foundation of engineering structures. Deep foundations are recommended for buildings in this area through pilling to the competent layer.

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