Constraining Causes of Structural Failure Using Electrical Resistivty Tomography (ERT): A Case Study of Lagos...

Article · January 2010

DOI: 10.4133/1.3445528

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CONSTRAINING CAUSES OF STRUCTURAL FAILURE USING ELECTRICAL RESISTIVTY TOMOGRAPHY (ERT): A CASE STUDY OF LAGOS, SOUTHWESTERN, NIGERIA

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ABSTRACT

The phenomenon of building collapse in recent times has become a source of national concern. Particularly alarming is the situation in Lagos, the commercial nerve center of Nigeria. Several attempts made to proffer solution to this excluded geophysical investigations, as general opinion did not support subsurface geology as being responsible. However, 2-D and 3-D electrical resistivity surveys were carried out using wenner electrode configuration with 64 electrodes connected to a multi-core cable, along three (3) profiles of 260 m length at an inter-electrode spacing of 4m. Resistivity measurements were taken alongside with Induced Polarization measurements using the same electrode configuration. The survey was conducted round to cover all the areas where distress in building structures is noticeable. The 2-D and 3-D electrical resistivity and IP images for the three profiles revealed that the main cause of structural defect in buildings around the area is the subsurface geology, contrary to general opinion which favours insufficiency and/ or lack of genuine building materials. From the results, it is quite obvious that the entire land mass of the study area is underlain by materials of very low resistivity values below 30 Ωm at the near-surface depth of 5 m down to above 30 m. Local high resistivity in the near surface material is due to either the effect of sand-filling for road network and/or the presence of exotic highly resistive concrete materials used to reclaim land. The IP inversion models help to delineate clay formation from sandy formation filled with saline water. The high IP signals in the subsurface mainly confirm the presence of clayey formation.

Key Words: Electrical Resistivity Tomography, Induced Polarization, Clay/Peat Formation, Foundation Investigation, Distress Building and Defective Structures.

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INTRODUCTION

The present work is aimed at showing the efficiency of 2-D and 3-D Electrical Resistivity Tomography (ERT) in probing the subsurface soil for foundation investigation. Many works have been done to establish a relationship between soil engineering test and ERT data (Israil and Pachauri, 2003; Cosenza et al., 2006; Gay et al., 2006). Also it has been discovered that 2-D ERT method is cost effective, efficient and less time consuming in geotechnical investigation than most geotechnic tests (Sudha et al., 2009). Another important advantage of ERT is that it produces continuous information of the subsurface and probes into several meters below the surface whereas, engineering soil test is a point investigation and does not go beyond a few meters below the surface. Interpretation of electrical measurement can give an understanding of the subsurface composition (geology), depth to competent layer (soil) and help to proffer safe measure for construction of different categories of buildings. The length of the pipe that must be sung to hold the foundation of a building could be determined from electrical resistivity survey. Lack of such approach led to partial collapse of big building structure as previously reported by Folorunso (2009) and Ayolabi et al., (2009a).

The parameters commonly studied in geotechnical tests are the grain size, soil strength and the number of blows (N-values). Though literature reported that the relationship between electrical parameters such as chargeability, resistivity and N-values is poor (Giao, et al., 2003; Sudha et al., 2009), we know this cannot be so between electrical properties on one side and grain size distribution, degree of saturation, porosity and cementation, on the other. Thus, in the present work, ERT data were complemented with Induced Polarization data to evaluate the cause of distress in buildings around the study area.

The theory of electrical resistivity suggests that electric current flows in the subsurface soil by electrolytic rather than electronic processes (Kearey et al, 2002). Hence, porosity is the major control of resistivity of rocks, and that resistivity generally increases as porosity decreases. Porosity and cementation, on the other hand, are related. It then means that electrical resistivity could be used to determine the degree of cementation to better characterize the subsurface soil for engineering foundation. Another important factor in knowing soil strength is the amount of fine (clay) present. Many authors have equally reported the relationship between the duos such that clay content in soil affects both soil strength as well as its resistivity (Sudha et al., 2009). Clay has very low electrical resistivity (Zhdanov and Keller, 1994); therefore, its contents in the soil may change the relationship between electrical parameter and soil strength (Sudha et al., 2009).

The present paper reports recent 2-D and 3-D Electrical Resistivity and IP surveys in a popular area within the Lagos metropolis where there are large-scale distress in buildings and even complete collapse of some. The only challenge the present study would have faced is differentiating between clay formation and saline water. This was taken care of by the IP measurements which differentiate moist clay formation and saline sandy formation from the IP response (Sastry and Tesfakiros, 2006, Ayolabi et al., (2009b).

GEOMORPHOLOGY AND GEOLOGY OF THE AREA

The area lies on latitudes 726350 to 727000 N and longitudes 874300 to 875350 E (UTM coordinate units). The total area cover is approximately 46.8 square kilometers (Fig 1). The topography is undulating and generally looks like a subsidence relative to Lagos landmass. Incidentally, buildings structures in the area are also subsiding, thereby typifying the area as an active region of mass subsidence. Surface water flow is highly impaired by the poor drainage channels that characterize the whole area since water from the neighbouring area flows in to Gbagada, being a valley. This leads to flooding, most especially during the rainy season.

The geology of Lagos was extensively studied alongside the geology of the Nigerian portion of Dahomey basin by many researchers (Jones and Hockey, 1964; Omatshola and Adegoke, 1981; Agagu, 1985; Enu, 1990; and Nton, 2001). The oldest formation identified in Dahomey basin is the Abeokuta formation (Jones and Hockey, 1964). This was upgraded to a group status with three formations by (Omatshola and Adegoke, 1981), comprising Ise formation having a conglomeratic and grity base overlain by coarse to medium grained sandstone with interbeded kaolinite; followed by a coarse to medium grained sandstone with interbeded shale, siltstone and claystone, having a sandy facies that is tar-bearing while the shale is organic-rich, called Afowo formation (Enu, 1990); overlain by Araromi formation, which is the youngest in the group: a Cretaceous sediment made of fine to medium grained sandstone at the base, overlied by shale, siltstone with interbeded limestone, marl and lignite. Abeokuta group is overlain by Ewekoro formation. This formation is made of a shaly limestone unit (Adekoge, 1977) reported to be highly fossiliforous (Jones and Hockey, 1964) assigned with the age of Paleocene. The formation is Akinbo which is composed of shale and clay sequence (Ogbe, 1972) belonging to Eocene age. Oshoshun is the next formation comprising pale greenish grey laminated phosphate and glauconitic shale of Eocene age. This is overlain by massive yellowish and poorly consolidated cross-bedded sandstone called Ilaro formation. The youngest formation in the basin is the Benin formation, also known as the coastal plain sands (Jones and Hockey, 1964). It comprises poorly sorted sands with lenses of clays belonging to Oligocene to Recent.

Lagos belongs to the coastal plain sand formation which is made up of loose sediment ranging from silt, clay and fine to coarse grained sand (Fig 2). The exposed rock unit in the area consists of poorly sorted sands with lenses of clays. The sands are in part cross bedded and show transitional to continental characteristics according to Jones and Hockey (1964), Omatshola and Adegoke (1981), Agagu (1985), Enu (1990) and Nton (2001). The age Oligocene to Recent was assigned to this formation on the basis of fauna contents.

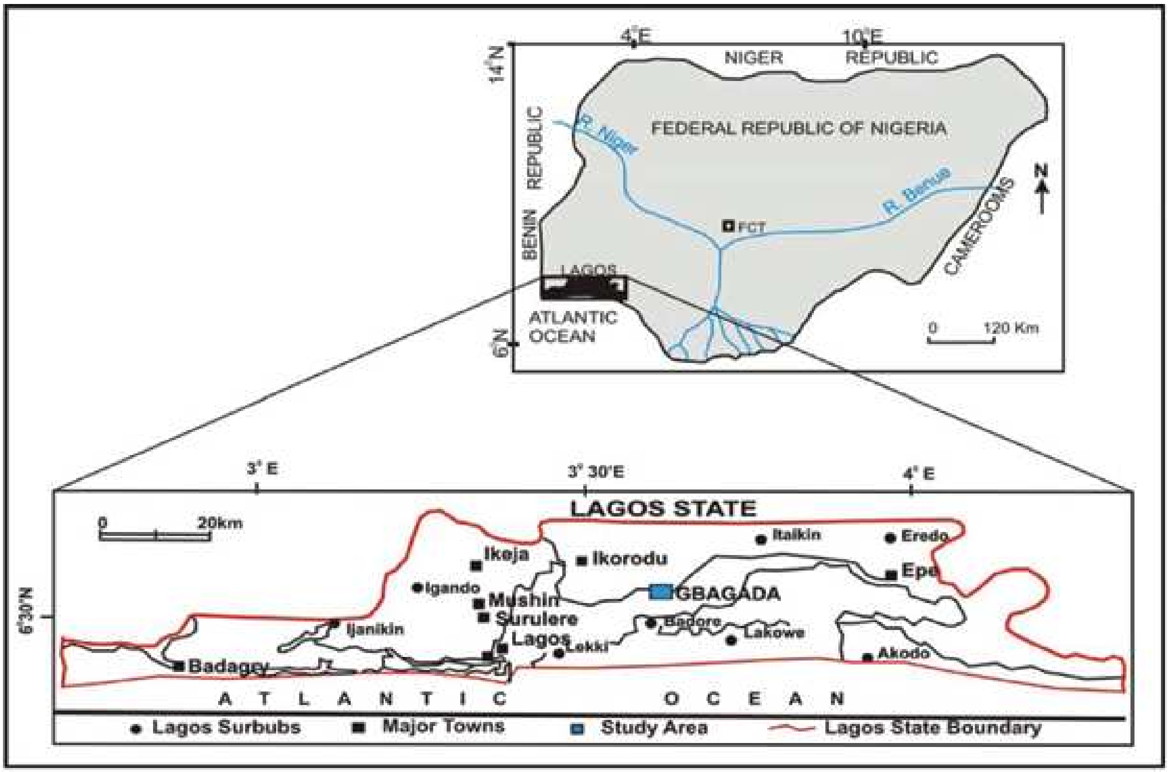

__FIGURE 1.__ Location Map Showing Gbagada with Nigeria Map Inset

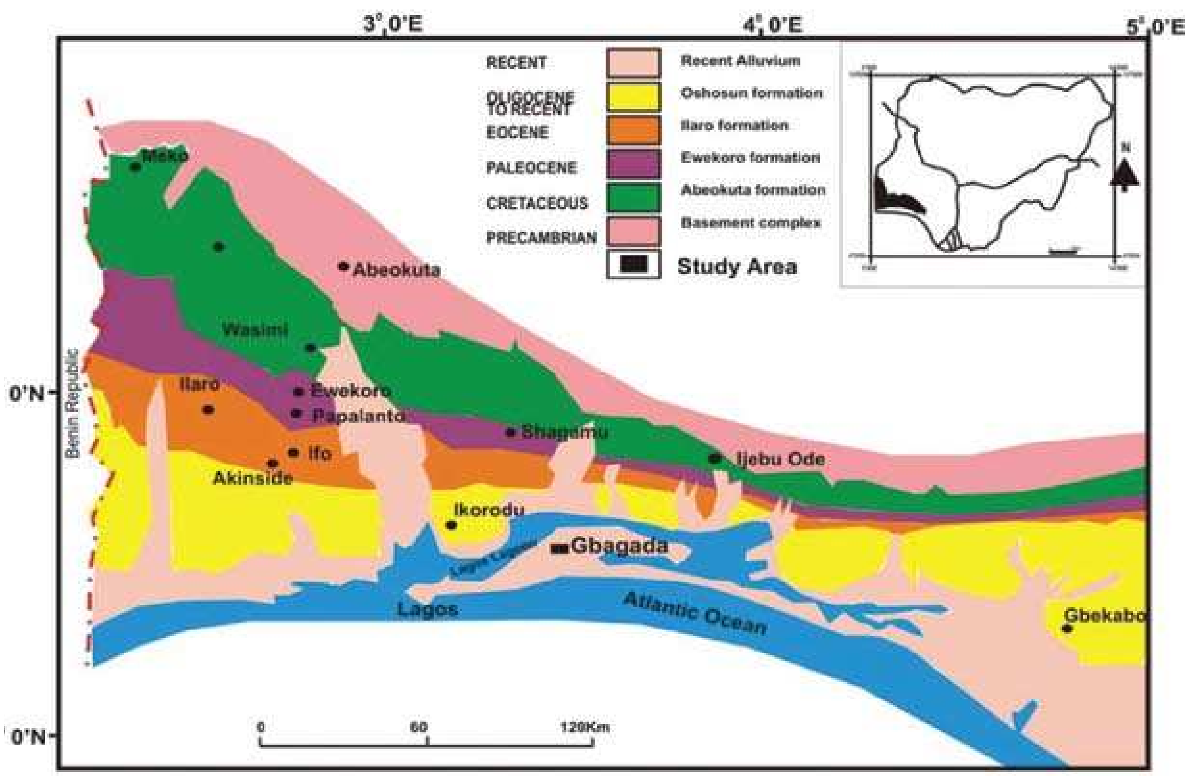

__FIGURE 2.__ Geological Map of Eastern Dahomey Basin (Modify After Billman, 1992)

THE PROBLEM

The major challenge building structures in Lagos are facing may be attributed to the subsurface geology of the city being a loose unconsolidated sediment. During deposition of sediment, plant and debris are equally deposited. Another regime of sedimentation where other materials are deposited on top of previously deposited ones occurs. In such cases, the plant and debris become a peat. This problem is prominent in some part of Lagos such as the study area – Gbagada.

Gbagada is a popular area in the Lagos metropolitan city that hosts residential, industrial, institutional and religious buildings. It accommodates a sizeable number of people among the over 15 millions dwellers in Lagos. The incessant building collapse in Lagos has assumed an alarming dimension in recent years. Properties worth millions of naira and lives of people have been lost to building collapse in various parts of the city (Fig 3), hence the necessity to find a more dependable technique of characterizing the subsurface soil prior to building construction works.

***FIGURE** 3. A Scene of Collapsed Building in Lagos (Source: The Nation, 27 March, 2009)*

A reconnaissance survey conducted recently in the study area shows that almost all the houses are structurally defective. Some buildings are completely submerged in the sand; some are tilted, while storey buildings have their down-stairs completely sunk into the subsurface, leading to total evacuation (Fig 4).

Many a time, when building collapses, an outpour of blames is directed at the building engineers for using inappropriate, inadequate or inferior materials. However, recent scientific study has proven this wrong as magnificent building complexes are found constructed on faults and buried river channel (Folorunso, 2009). Most engineering soil tests carried out prior to building construction are inadequate in that they are point investigations rather than continuous imaging of the subsurface. A similar problem is exhibited by the use of vertical electrical sounding (VES) in engineering survey (Ayolabi et al., 2009a). Thus, engineering soil tests must be carried along with 2-D and 3-D electrical resistivity measurements for better characterization of the subsurface soil prior to any kinds of construction work.

FIGURE 4. *Different Degrees of Structural Instability Observed on Buildings in the Area*

INVESTIGATIVE METHODS

The methods adopted in the field investigation are electrical resistivity tomography (ERT) technique for the 2-D and 3-D and IP tomography. The ERT and IP investigations were carried out in three locations within the area, including a site being developed as a housing estate (profile 3). The synoptic view of data acquisition and profile lane and direction at Gbagada is shown in Fig 5.

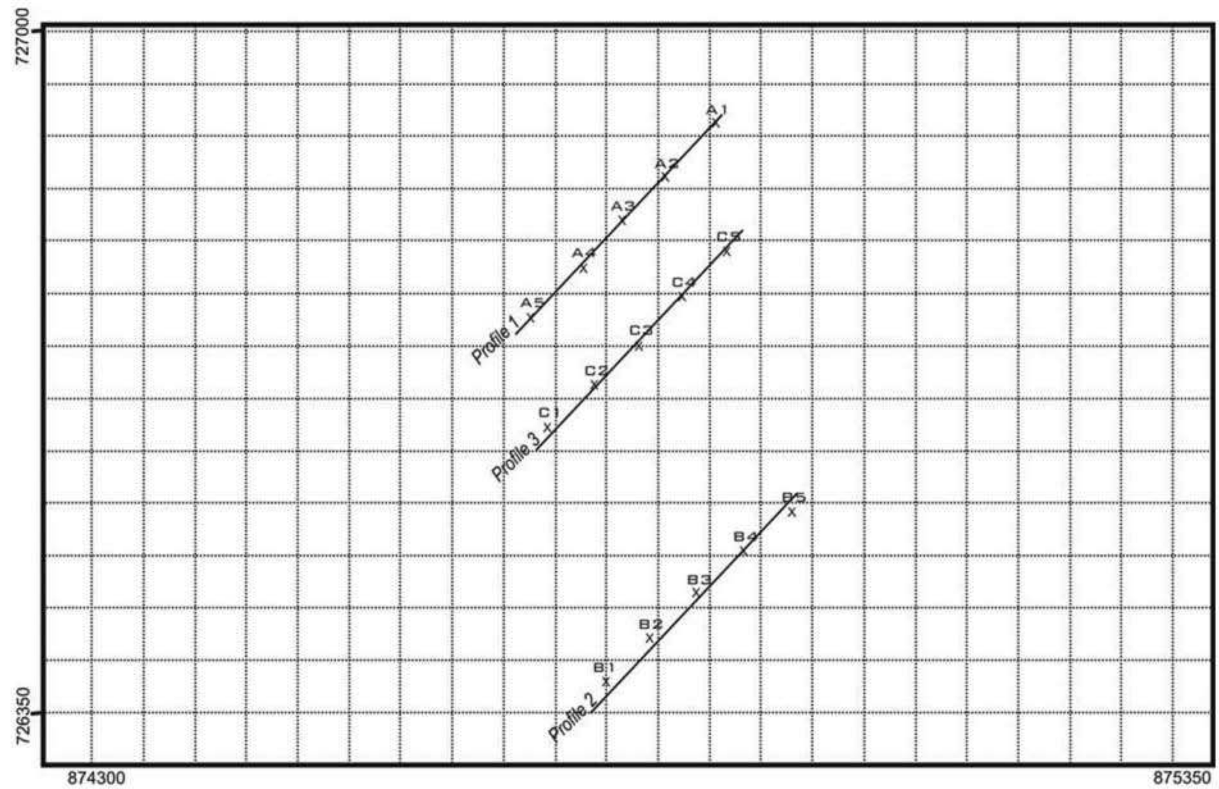

FIGURE 5. *The synoptic view of data acquisition and profile lane*

GEOELECTRICAL INVESTIGATIONS

ELECTRICAL RESISTIVITY TOMOGRAPHY METHOD

ERT survey data were acquired using ABEM SAS-1000 Lund Imaging System with 64 electrodes connected to a multi-core cable (Griffiths and Baker, 1993). With this equipment, consecutive readings were taken automatically and the results averaged continuously. SAS results are more reliable than those obtained using manually operated single-shot systems (ABEM, 2008), because the latest equipment is an automated machine connected with a laptop with an electronic switching unit that automatically selects the relevant four electrodes for each measurement (Loke, 2000, 2004). Wenner electrode configuration was chosen for its high resolution and depth of penetration (Loke, 2004). The array was popularized by the pioneering work of the University of Birmingham research group (Griffiths and Turnbull, 1985 and Griffiths et al., 1990). The total length of each prolife was 260 m at an inter-electrode spacing of 4m. The data was processed and inverted using Earth Imager inversion software. The program generates the inverted resistivity-depth image for each profile line. The software was used for both 2-D and 3-D ERT and their corresponding IP tomographs (Figs 6 and 7). Global Positioning System (GPS) was used to obtain the coordinates at survey stations.

IP SURVEY METHOD

Induced Polarization data were also acquired using the same SAS-1000 ABEM Terrameter with the same electrode configuration in the multi-electrode resistivity meter system. Murali and Patangay (2006) observed that it is a common practice to measure the IP sounding along with resistivity for correct interpretation of field data. Measuring IP with ERT enables us to interpret the data in 2-D and 3-D as well as using the Earth Imager software developed by AGI Austin. This robust attempt is one of the more recent developments in the instrumentation of electrical imaging surveys (Loke, 2004).

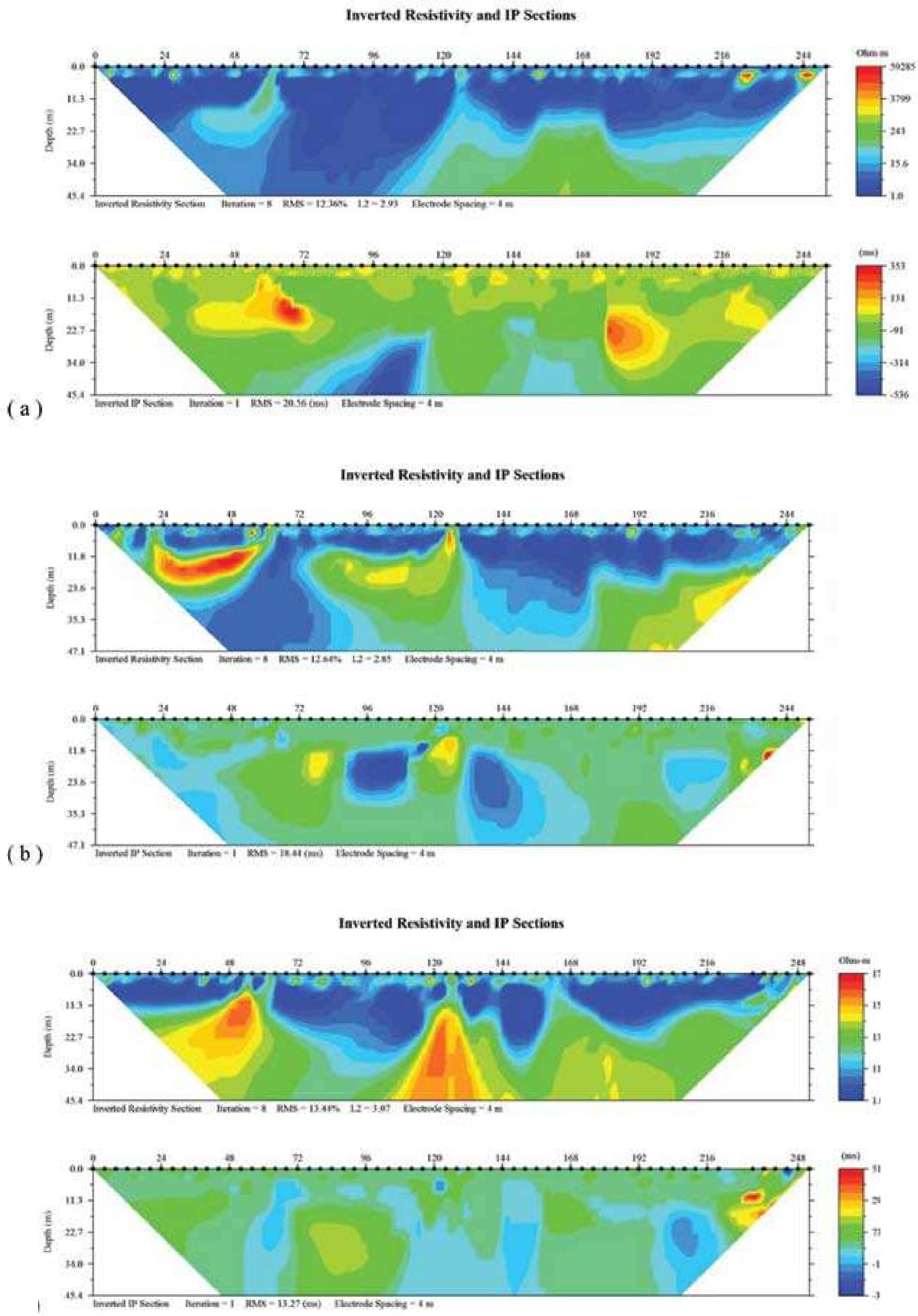

FIGURE 6. *The inverted resistivity and IP sections along ERT lines (a) Profile 1; (b) Profile 3; and (c) Profile 2.*

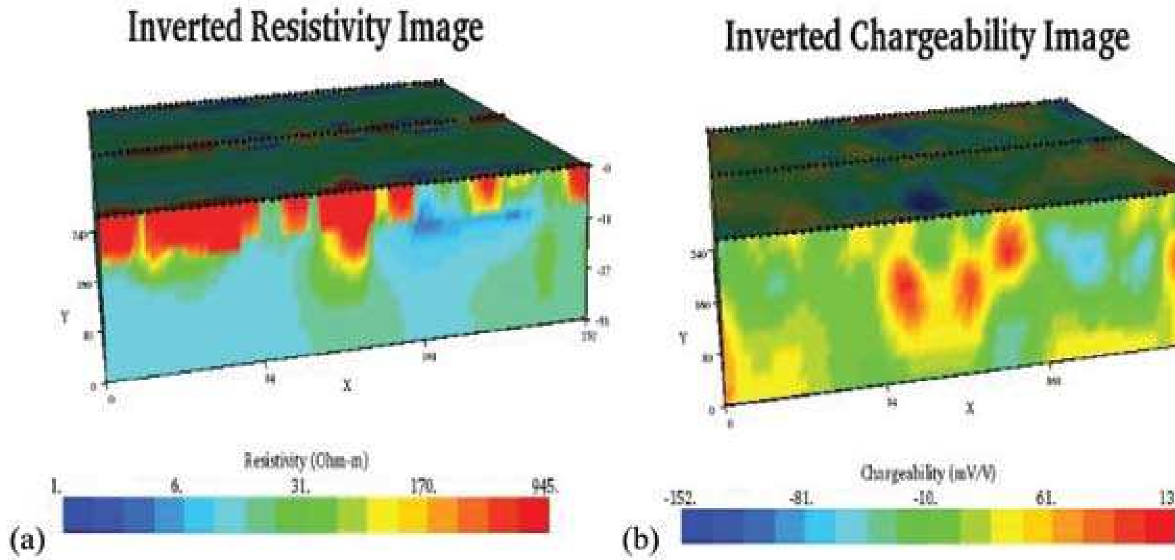

FIGURE 7. *3-D resistivity and IP block measured in the study area*

RESULTS AND INTERPRETATION

2-D ERT RESULTS

The problems of non-uniqueness, equivalence and suppression are well known in 1-D sounding. Similar problems, in different forms, also occur in 2-D and 3-D modeling. (Loke, 2004). These result in two different targets giving the same signal, as in the case of clay and groundwater (Kearey et al., 2002; Ayolabi et al., 2009b). The best way to reduce such ambiguity is to use additional data/information from other sources (Sudha et al., 2009). We use IP data to constrain and identify clay from sandy formation holding saline water. The IP signal from clay horizon is relatively high (Ayolabi et al., 2009b), while signal from groundwater in a sandy layer is nearly zero (Murali and Patangay, 2006). In addition, the RMS values below 14% obtained in the three profiles indicate that the data are fitted with the computed response and the average error floors is less than 14% in all the data. The inverted resistivity and IP sections for the three profiles are shown in Fig 8 (a to c).

The distribution of resistivity in the subsurface soil of the study site shows a wide variation of resistivity of soil at different depths along each profile line, starting from a low value of 1Ωm to a higher value of 59285 Ωm. In profile 1, the top layer is characterized by relatively high resistivity of a very thin thickness less than 4m. This could probably be due to sand-filling along the profile line while pockets of high resistivity materials near the surface could be as a result of concrete boulder materials used during land reclamation process, which are now buried in the sediment (e.g. electrode positions 224 and 244 m), (Fig 8a). The decrease in resistivity at depth below the top soil indicates the presence of saturated soil interpreted as peat material – fine grained silty soil with decomposed organic matters (less than 10 Ωm). The peat (blue colour) (Fig 8a) is encountered at almost all level below the topsoil to a depth of 45m. The subsurface soil under the profile is grossly incompetent to hold any building

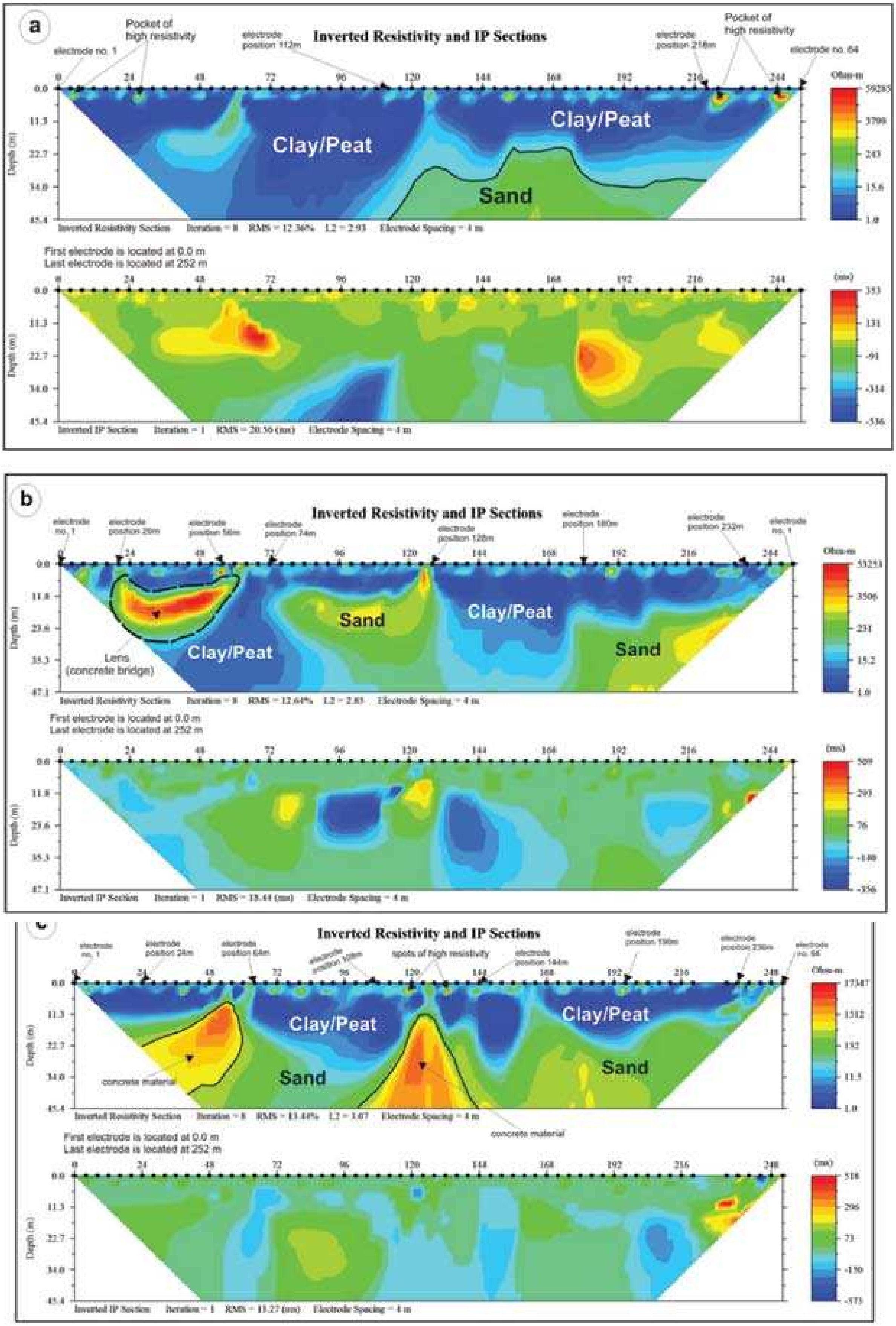

FIGURE 8. *The Resistivity-Depth Model and IP Sections along the ERT Lines (a) Profile 1; (b) Profile 2 and (c) Profile 3*

unless a competent layer is struck definitely far below the current depth of penetration. However, a fine sand formation (100 to 400 Ωm) was encountered at 20 m depth below the surface at electrode positions 112 – 220 m which could have good engineering properties for building construction. The IP inversion result equally buttresses the presence of water-saturated clayey formation dominating the subsurface soil of the study area.

Resistivity-depth model obtained in profile 2 (Fig 8b) is similar at near surface with that of profile 1 as the top soil reveals sand-filling effect at a depth less than 4m with resistivity of <100 Ωm. However, there is a 'lens' of very high resistivity (between 250 to 2500 Ωm) materials encountered at about 10m below the surface between electrode positions 20 and 60 m. The very high resistivity structure could likely be an earlier concrete bridge put in place during construction work in this area, which has now sunken deep into the soil, confirming the weak nature of the subsurface soil materials in the area. At electrode positions 74 to128 m, a sandy formation was encountered with high resistivity value between 230 and 1300 Ωm. In fact, the IP section with very low chargeability (-350 to -140 mV/V) further confirms the sandy formation. Subsurface soil toward the end of the profile at a depth of 24 m downward exhibits another stable soil of high resistivity value similar to the one just described above, which is interpreted as a sandy formation. All other areas are marked by relatively low resistivity (> 30 Ωm) (blue colour), indicating the presence of fine soil material – clay/peat – (e.g., electrode positions 0 – 112 m, 132 – 180 m, and 64 – 120 m in profiles 1, 2 and 3 respectively (Fig 8 a-c).

Fig 8c indicates the similar inverted resistivity and IP sections obtained as resistivity-depth model in the previous profiles, especially in the topsoil with high resistivity (> 130 Ωm) that reflects exotic materials used for road construction; the road serves as the platform for this survey. Similarly, 'spots' of high resistivity (e.g., electrode positions 40, 80, 120, 132, and 196 m) in the near surface come from exotic concrete materials used in reclaiming land in the area. However, peat and clay formation underlay the top resistive layer. The very low resistivity value (> 20 Ωm) of these materials indicates the presence of fine soil material and increase in the percentage of clay in soil matrix. These are silt and clay in full saturation condition (marked by high IP values above 70 mV/V). Such high IP value has been attributed to clay formation by Ayolabi et al., (2009b). Below the clay horizon are highly resistive reef-like structure materials with resistivity ranging between 500 and 2000 Ωm at electrode positions 24 to 64 m and 108 to 144 m (Fig 8c). These are interpreted to be the concrete and materials from collapsed buildings that were previously used to reclaim land in the area. These exotic materials have sunken due to density and formed a wavy topography as displayed by resistivity section along the profile. It is known that bridge surroundings are sand filled after construction to enhance accessibility. This was also revealed by a drop in the resistivity values (< 300 Ωm) around the suspected bridge (electrode positions 56 to 108 m and 144 to 236 m).

From the resistivity and IP inverted sections, it was also noted that areas of high resistivity values correspond with areas of low IP value and vise visa (e.g., between electrode positions 4 to 112, 88 to 112, and 72 to 108 m on profile 1, 2 and 3 respectively), (Fig 8 a-c). This was the general trend in the three inverted sections. This observation helps to confirm the consistency and error-free of the process of data acquisition. It could also be used as reference to the inverse relationship between resistivity and IP values.

3-D ERT AND IP RESULTS

From the 3-D tomography images for the three profiles (Fig 9a and b), it was quite obvious that the entire land mass of the study area is underlain by materials of very low resistivity values below 30 Ωm from the depth of less than 7 m (Fig 9a). Local high resistivity in the near surface materials is due to either the effect of sand-filling for road network and/or the presence of exotic highly resistive materials. The IP inversion model (Fig 9b) shows high signal values in the subsurface. This is mainly an indication of clayey formation, thereby differentiating it from saline water.

CONCLUSIONS

Our study has demonstrated the practical application of both 2-D and 3-D ERT and IP tomography in characterizing the subsurface soil for engineering investigation. Interpretation of both ERT images has revealed that the subsurface soil at the study site is mainly fine/clayey soil in oversaturation condition with a low resistivity of less than 30 Ωm. The low resistivity indicates the conductive capacity of the associated water. Maximum depth of penetration in all the 2-D profiles is put at 47 m while the 3-D interpretation gives a deeper depth of 55 m. Local high resistivity in the near surface material is due to either the effect of sand-filling for road network and/or the presence of exotic highly resistive materials used during land reclamation process. To separate saline formation from clayey formation, IP 2-D and 3-D tomography images were acquired which confirm the low resistivity regions as saturated clayey formation. All the profiles represent the geologic conditions of the entire Gbagada area as a region of intense subsidence covered by oversaturated clay/peat formation. Thus, building failure in this area results from the incompetent nature of the subsurface soil.

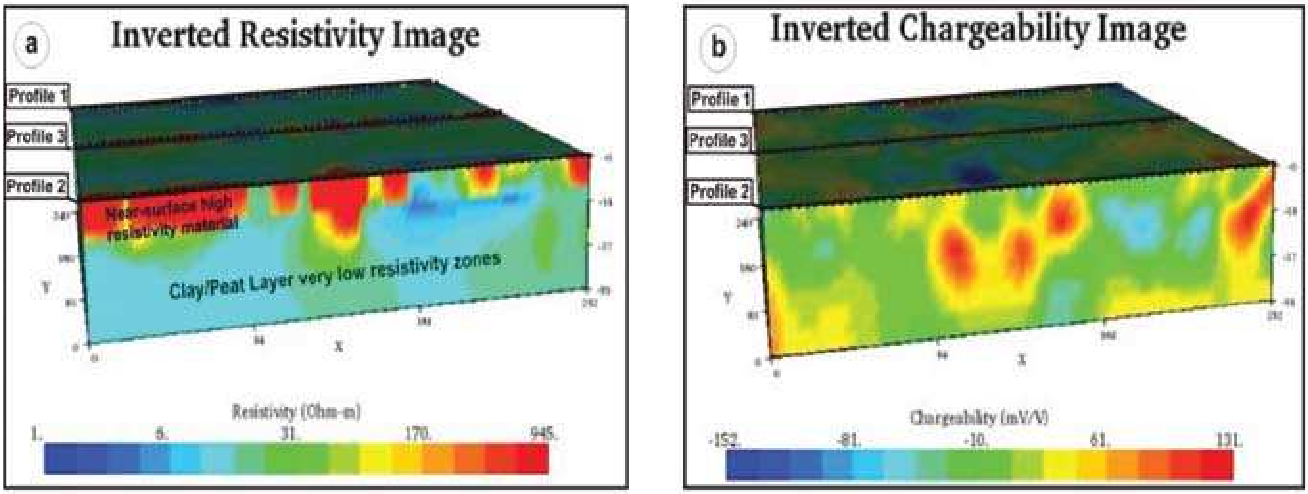

FIGURE 9. *3-D IP Section for the three Profiles*

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Manuscript received from:
- the authors on 11.5.10
- the Review Committee on 6.10.10

Παραλαβή εργασίας:
- αρχική από τους συγγραφείς στις 11.5.10
- τελική από την Κριτική Επιτροπή στις 6.10.10