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Geophysical Investigation of Structural Failures Using Electrical Resistivity Tomography: A Case Study of Buildings in FUPRE, Nigeria

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Abstract

Vertical Electrical Sounding was conducted around four buildings in Federal University of Petroleum Resources Effurun (FUPRE), Nigeria. This is to delineate the soil types and unravel the subsurface conditions responsible for palpable cracks on these buildings. Schlumberger electrode array was employed for data acquisition. Optimization of measured field and calculated apparent resistivity data and interpretation of electrical resistivity tomography (ERT) generated using RES2DINV software revealed a variation in soil resistivity and type. Two major sub-soil types, clayey-sand and sand, from top to bottom underlie the study area. The clayey-sand is observed to exhibit low resistivity values ranging between 250 and 953Ωm while the sand has resistivity values ranging between 1324 and 2957Ωm. The results reveal that there is frequent intercalation of clay within the sands at depths ranging from 0.1 to 2.0m where the foundations of these buildings are located. The presence of clays in the sands is indicative of possible seasonal moisture and volumetric expansion and shrinkage and uneven ground settlement underneath these buildings. Thus, foundations of buildings should be reinforced by piling to depths ≥2m (6ft) below the ground surface so as to avoid this zone, especially underneath the foundations of multi-storey buildings.

Keywords: Cracks, Electrical Resistivity Tomography (ERT), clayey-sand, sand, expansive soil, buildings.

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1. Introduction

Some buildings in Federal University of Petroleum Resources Effurun (FUPRE) are experiencing various cracks few years after they were constructed in 2007, despite the strength of the reinforcements of the foundations. Some of these cracks are so severe on the walls that one will nearly see through to the next room. This has become a serious concern to the University Community in view of the increasing population and the safety of lives and property of staff and students occupying these buildings in case of any collapse.

Certain soil types experience seasonal moisture and volumetric changes which are among the main factors affecting the stability of buildings in most parts of the world. Clay soils expand by volume several times when saturated or shrink drastically when dehydrated (Egwuonwu and Sule, 2012). Expansive soils derive their characteristics from the presence of swelling clay minerals. As the clay minerals get wet, they absorb water molecules and expand. Conversely, as they get dry, they shrink, leaving large voids with air entrapment in the soil (Taboada, et. al., 2001). Swelling soils lift up and crack lightly-loaded, continuous strip footings and frequently cause distress in floor slabs. During the process of ground settlement, the expansion and shrinkage of clayey soils cause cracks on buildings soon after construction. So, understanding the dynamics of these soils is very important in tackling geotechnical challenges commonly associated with the construction of foundations of buildings, bridges, dams or roads.

Several studies using different methods such as laboratory measurements of Standard Penetration Test, plastic limit, plasticity index, liquid limit, immersing remolded soil sample and measuring its volume change, geophysical investigations and so on have been conducted by various researchers [(Olorunfemi, et. al., 2002), (Akintorinwa and Adeusi, 2009), (Olorunfemi, et. al., 2005), (Akintorinwa, et. al., 2011), (Salami, et. al., 2012), (Fatoba, et. al., 2013), (Olayanju, et. al., 2017) and (Adewuyi and Philips, 2018)].

Consequently, this research investigates the soil types and conditions in FUPRE employing 2D Electrical Resistivity Tomography (ERT) to reveal the root cause(s) of cracks on walls and prevent further cracks on new buildings that will be constructed in the campus in the future.

2. Location, geomorphology, climate and brief geology of the study area

2.1 Location

The study area is located within the campus of Federal University of Petroleum Resources Effurun (FUPRE), Nigeria (Figure 1).

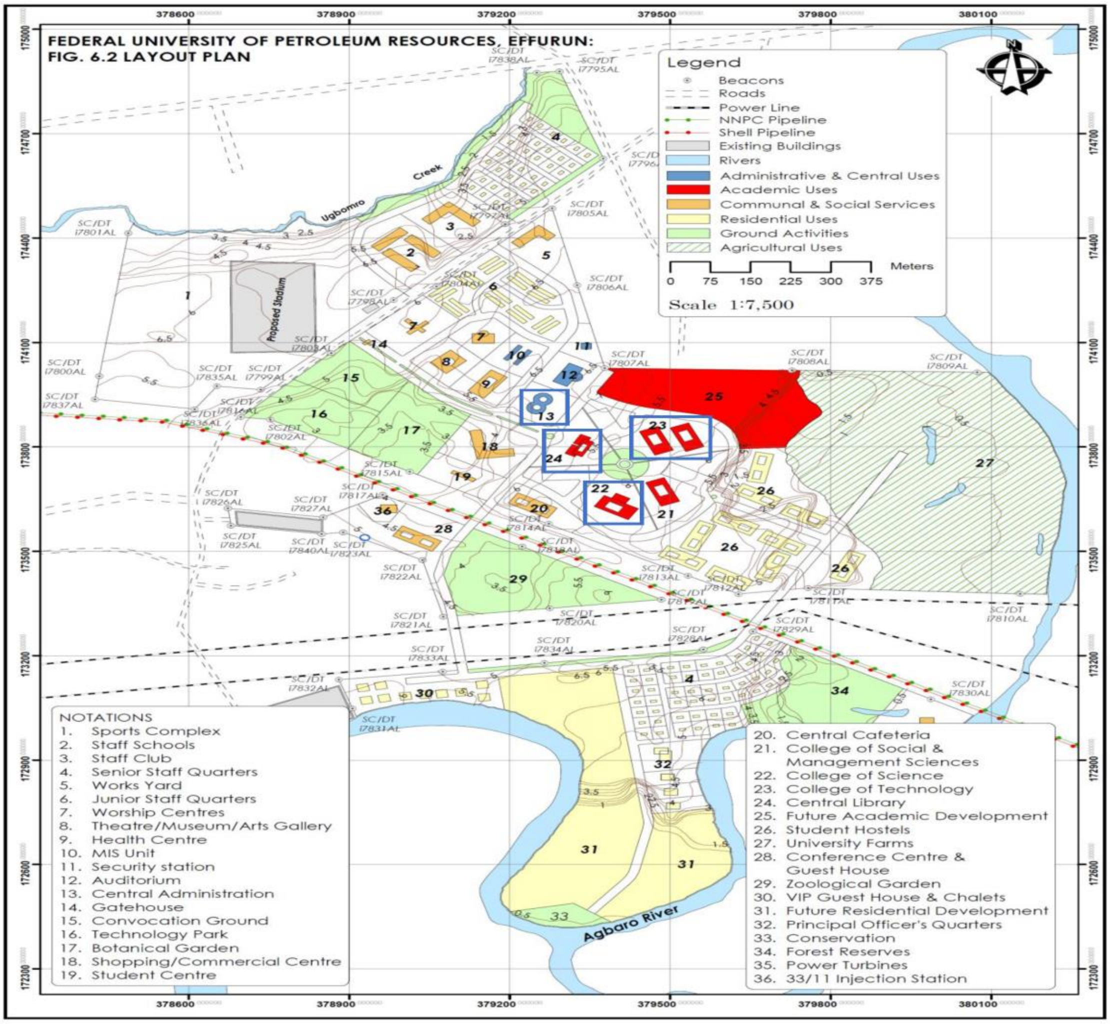

Figure 1: Map of FUPRE campus showing the study areas in blue rectangles.

2.2 Geomorphology and climate

The study area is found within the fresh water vegetation belt of rain and swamp forests which is thickly vegetated with grass, trees and creeping plants. It is a lowland with elevation less than 15m above sea level. It is a relatively flat terrain and it is drained by the Agbarho and Ugbomro Rivers. It is a hot/wet equatorial climate region made of wet and dry seasons. The climate is tropical equatorial type with mean annual rainfall greater than 300mm and mean temperature of about 28°C (Iloeje, 1981). The wet season begins from April and ends in September while dry season begins from October and ends in March. The area has a direct recharge from rainfall. The rate of infiltration and percolation is very high. The depth to water is high at a maximum of 5m below the ground surface in the dry season and less than 1m in the wet season (Akpoborie, et. al., 2000).

2.3 Brief geology of the study area

FUPRE is located within the Niger Delta which is situated on the continental margin of the Gulf of Guinea in equatorial West Africa between latitude 4°N to 7°N and longitude 5°E to 8°E covering an area of about 108,900km^2 (Whiteman, 1982). It extends from the Calabar flank and the Abakaliki Trough in eastern Nigeria to the Benin flank in the west and it opens to the Atlantic Ocean in the south. The development of Niger Delta resulted from the formation of Benue trough as a failed arm of a triple junction associated with the separation of African and South American Plates and subsequent opening of the South Atlantic (Whiteman, 1982). The Benue-Abakaliki trough was filled with sediments during the early Cretaceous time which later underwent folding, faulting and uplift with subsidence of the adjacent Anambra basin to the west and Afikpo syncline to the east during the Santonian. Niger Delta comprises three diachronous Units, Akata, Agbada and Benin Formations (Weber and Daukoru, 1975). It is underlain by Quaternary Warri deltaic sand (Etu-Efeotor and Akpokodje, 1990). The sediments overly the Coastal Plain sand comprising silt, sand and clay. The sands are loose, porous, poorly sorted and lateritic. Small amounts of gravels and thin clay horizons are sometimes present at greater depths (Avbovbo, 1978).

3. Methodology

3.1 Field data acquisition

The Vertical Electrical Soundings (VES) were conducted employing Ohmega Digital Terrameter (Figure 2). Schlumberger electrode configuration was employed for the data acquisition (Figure 3). Two current electrodes (AB) with a maximum separation of 40m were placed linearly at the same mid-point with two potential electrodes (MN) but at different distances from one another. The current electrodes were placed at equal distance, s from the mid-point of the configuration while the potential electrodes were placed at equal distance but at $a/2 < \mathbf{s}$. Different spreads of current electrodes AB were achieved, thereby resulting in different probe depths.

Figure 2: Instruments arrangement for the data acquisition.

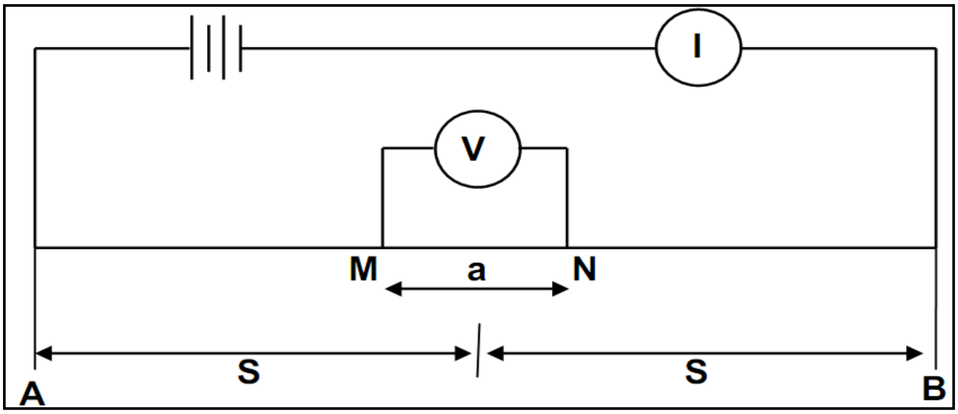

Figure 3: Schematic of Schlumberger array for data acquisition.

3.2 Sounding locations

The buildings under investigation are the Library, Administrative, College of Science and College of Technology Blocks constructed in 2007 (Figures 4 to 7). On the sides of each building, a total of four Vertical Electrical Soundings (VES) traverses were conducted amounting to a total of 16 VES locations.

3.3 Measured apparent resistivity, ρ_a

Apparent resistivities were obtained from field resistance values using the equation:

$$\rho_a = \frac{2\pi R}{k} \tag{1}$$

Where ρ_a is apparent resistivity, R is the measured resistance, AB is the distance between current electrodes, MN is the distance between potential electrodes and the geometric factor, k , is given as:

$$k = \left[\frac{1}{AM} - \frac{1}{AN} - \frac{1}{BM} + \frac{1}{BN}\right] \tag{2}$$

Therefore, ρ_a becomes:

$$\rho_a = \frac{2\pi R}{\left[\frac{1}{AM} - \frac{1}{AN} - \frac{1}{BM} + \frac{1}{BN}\right]} \tag{3}$$

3.4 Data optimization

The measured values from the field survey were optimized by computer program (inversion technique to generate smooth 2D models) to ensure that the measured resistivity agrees with the calculated apparent resistivity values. This optimization method basically reduces the difference between the calculated and measured apparent resistivity values by adjusting the resistivity of the models. A measure of this difference is given by the root-mean-squared (RMS) error. From the processed data, the depths and resistivity values were inferred for each location.

3.5 Data interpretation and electrical resistivity tomography modelling

Data interpretation was based on a 2-D model of the subsurface which consists of a number of rectangular blocks. Apparent resistivity conversion to the true resistivity and the subsequent inverse subsurface model was carried out using a resistivity 2D inversion (RES2DINV) software. Various vertical electrical sounding (VES) data were extracted from the 2-D resistivity data acquired from the study area. The data generated by the RES2DINV software was gridded to produce a 2-D Electrical Resistivity Tomography (ERT).

4. Results

Figures 8 to 23 show the 2D electrical resistivity tomography (ERT) for the 16 VES profiles around the Library, Administrative, College of Science and College of Technology Blocks. The figures show the measured apparent resistivity pseudo-sections, calculated apparent resistivity pseudo-sections and the inverse model resistivity sections produced after optimization to reduce the root-mean-square error between them. The inverse model resistivity sections are displayed as functions resistivity in Ohm-meter versus soil depth in metres and are inferred from the processed pseudo-sections. Resistivity values at various depths are determined from this inverse model resistivity. Table 1 is a summary of the interpretation of ERT for the four buildings.

4.1 Library block (LIB)

Figures 8 to 11 show the results for the Library building. Lowest resistivity values between 584 and 659 Ωm are observed at LIB 1 (Figure 8) in the deep near-surface layers (from 0.9 to >2.0m) and 660 and 707 Ωm at LIB3 (Figure 10) at a depth from 0.1 to 0.5m in the shallow near-surface layer. Soils within these zones are characterized as clayey-sand. Highest resistivities values between 2561 and >2877 Ωm are observed at LIB 2 (Figure 9) at depth from 0.5 to 1.0m in the shallow near-surface layer. Soil within this zone is characterized as sand.

4.2 Administrative block (ADM)

Figures 12 to 15 show the results for the Administrative Block. Lowest resistivity values between 262 and 394 Ωm were observed at ADM 4 (Figure 15) at depths from 0.1 to 0.4m and 406 and 625 Ωm at ADM 3 (Figure 14) at depths of from 0.1 to 0.4m. Soils within these shallow near-surface layers are characterized as clayey-sand. Highest resistivities values between 2798 and >2970 Ωm are observed at ADM 2 (Figure 13) at depth between 0.1 to 0.4m and 2683 and >2786 Ωm at ADM 1 (Figure 12) at depth between 0.3 to 0.5m in the shallow near-surface layers. Soil within these zones is classified as sand.

4.3 College of science block (COS)

Figures 16 to 19 show the results for the College of Science Block. Lowest resistivity values between 856 and 953 Ωm are observed at COS 1 (Figure 16) at depth from 0.1 to 0.3m in the shallow near-surface layer. Soil within this zone is classified as clayey-sand. Highest resistivities values are observed between 2470 and >2957 Ωm at COS3 (Figure 18) at depth from 0.1 to 0.5m also within the shallow near-surface layer. Soil within this zone is classified as sand.

4.4 College of technology block (COT)

Figures 20 to 23 show the results for the College of Technology Block. Lowest resistivity values between 250 and 399 Ωm are observed at COT 3 (Figure 22) at depth from 0.1 to 0.5m at the shallow near-surface layer. Soil within this zone is classified as clayey-sand. Highest resistivities values are observed between 1324 and >1480 Ωm at COT 2 (Figure 21) at the deep near-surface layer at depth from 0.7 to >0.99m). Soil within this zone is classified as sand.

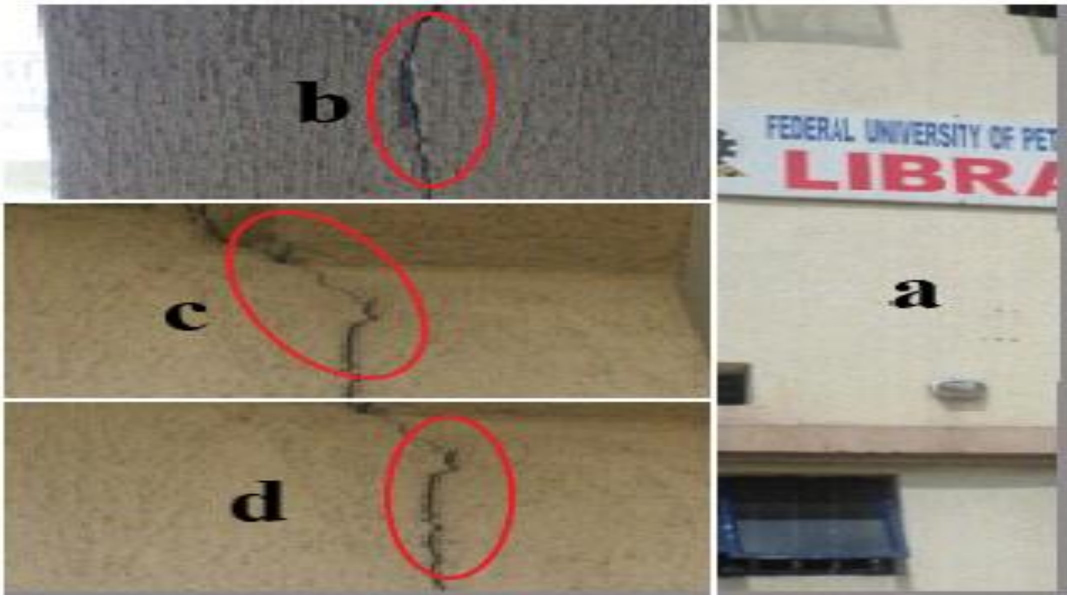

Figure 4: Library Building, showing the severity of some vertical cracks on parts of the building (a) part of the building under study (b) vertical cracks upstairs (c) and (d) vertical cracks downstairs.

Figure 5: Administrative Building, showing the severity of some diagonal cracks on parts of the building (a) parts of the building under study (b), (c) and (d) some diagonal cracks.

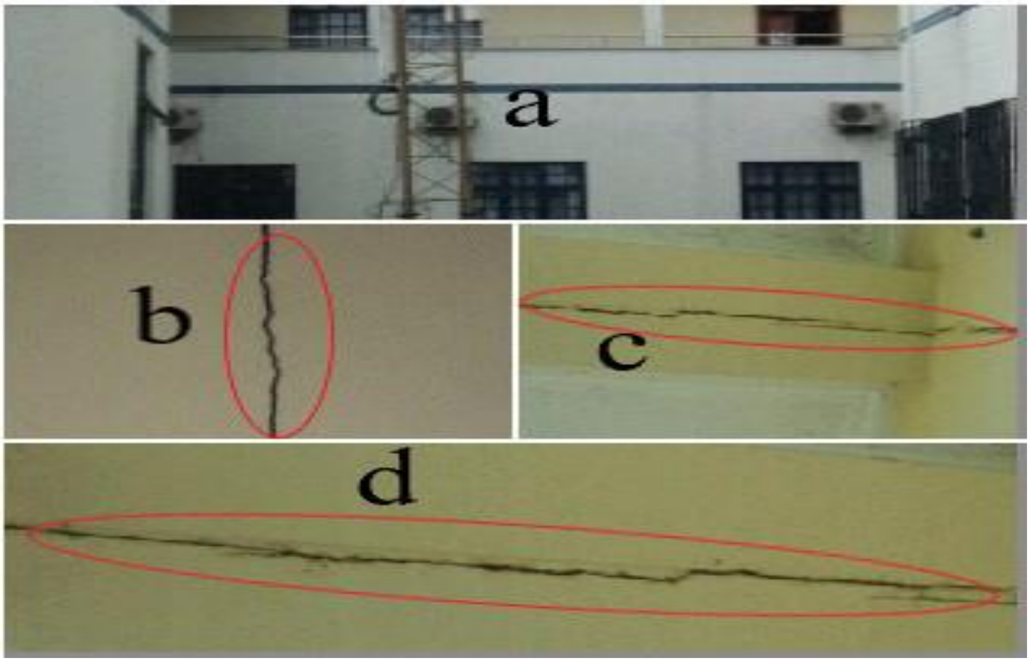

Figure 6: College of Science Building, showing the severity of vertical and horizontal cracks on parts of the building (a) part of the building under study (b) some vertical crack (c) and (d) some horizontal cracks.

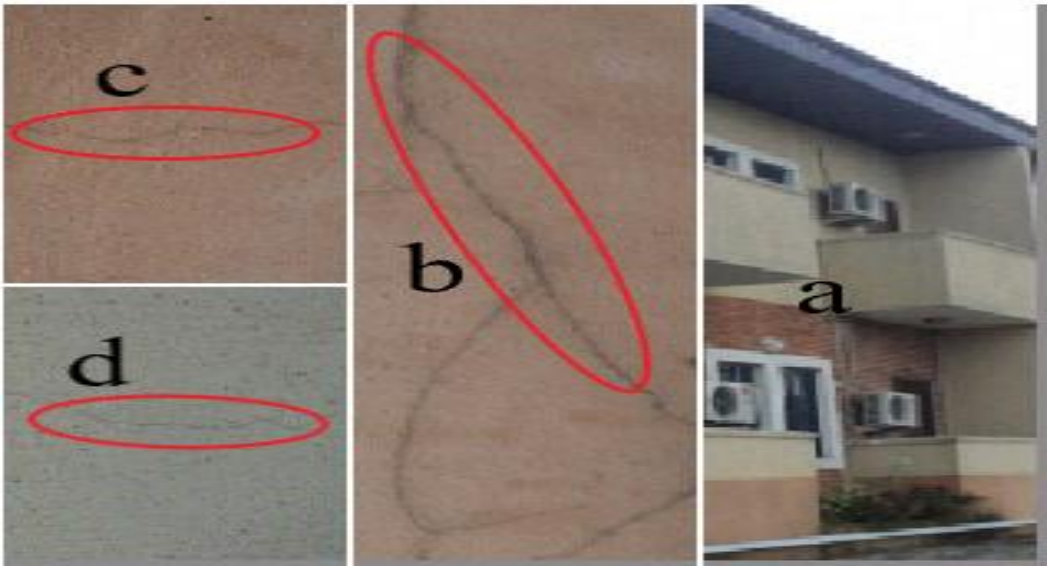

Figure 7: College of Technology Building, showing the severity of some diagonal and horizontal cracks on parts of the building (a) parts of the building under study (b) diagonal crack (c) and (d) horizontal cracks.

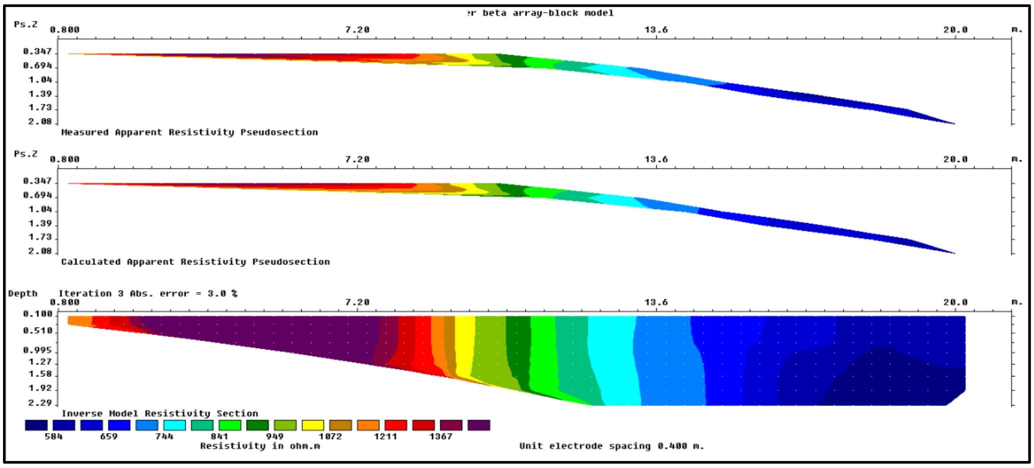

Figure 8: 2D Resistivity tomogram for profile LIB 1.

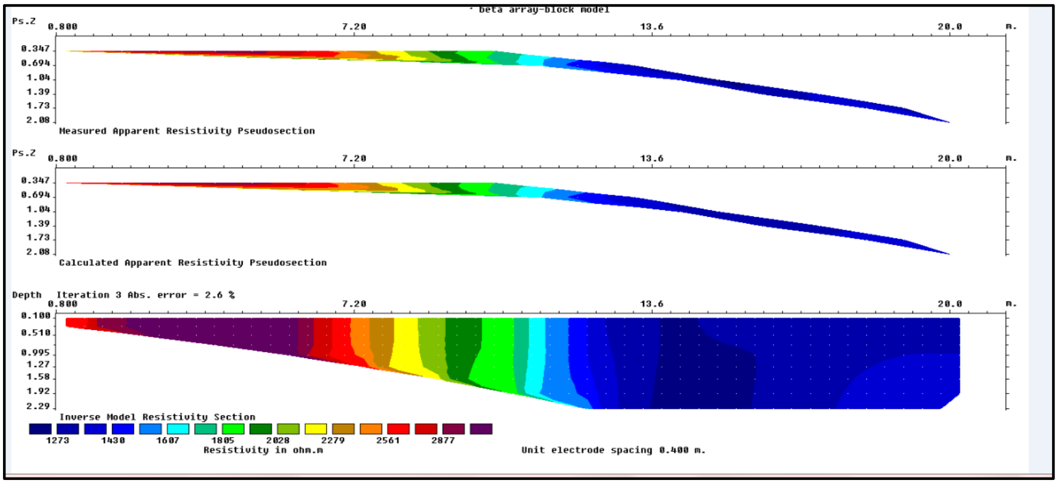

Figure 9: 2D Resistivity tomogram for profile LIB 2.

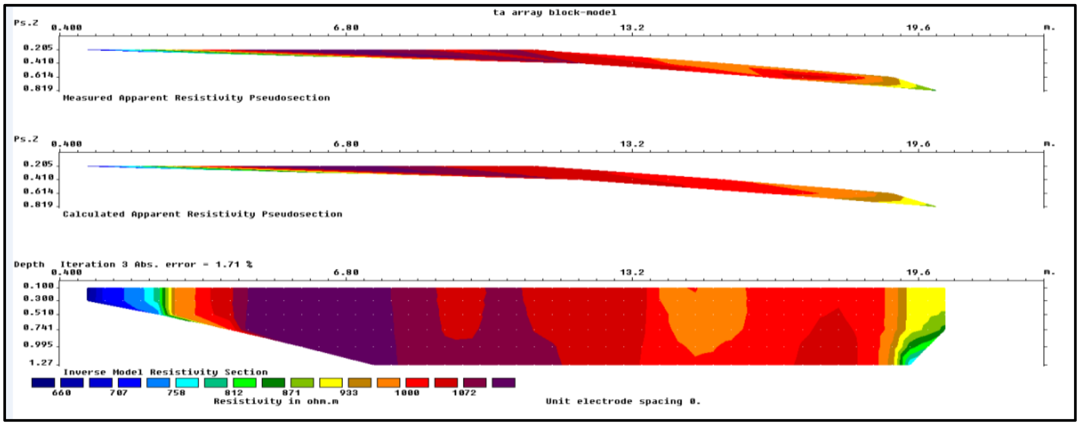

Figure 10: 2D Resistivity tomogram for profile LIB 3.

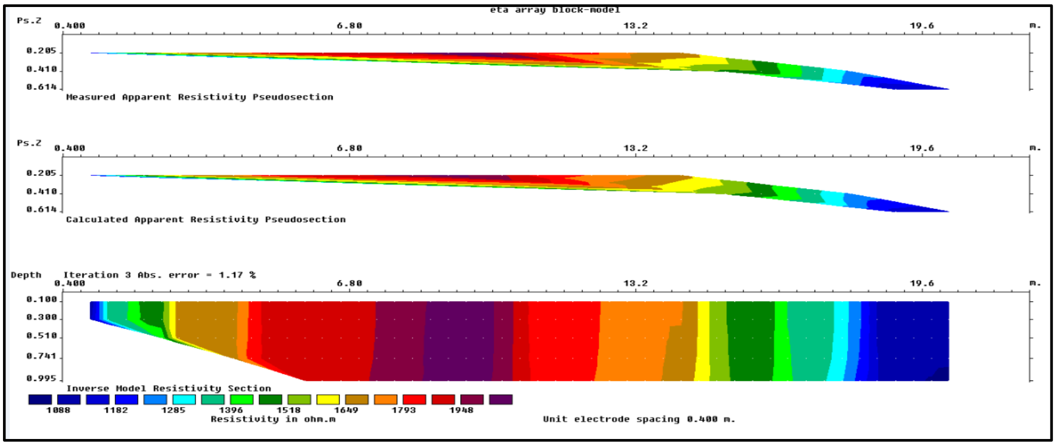

Figure 11: 2D Resistivity tomogram for profile LIB 4.

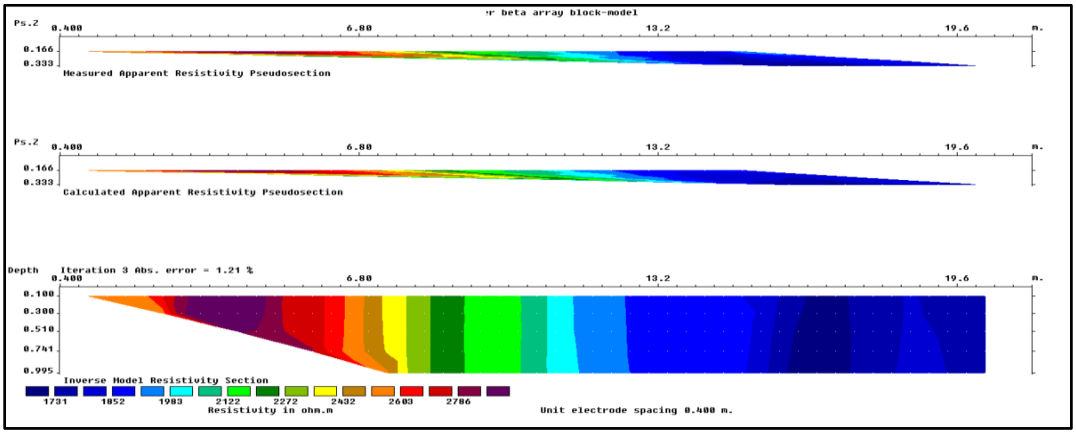

Figure 12: 2D Resistivity tomogram for profile ADM 1.

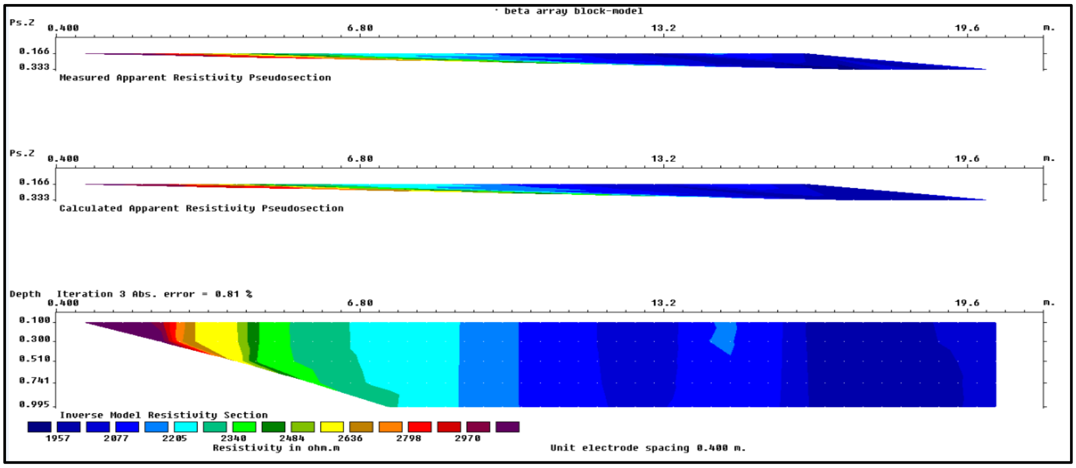

Figure 13: 2D Resistivity tomogram for profile ADM 2.

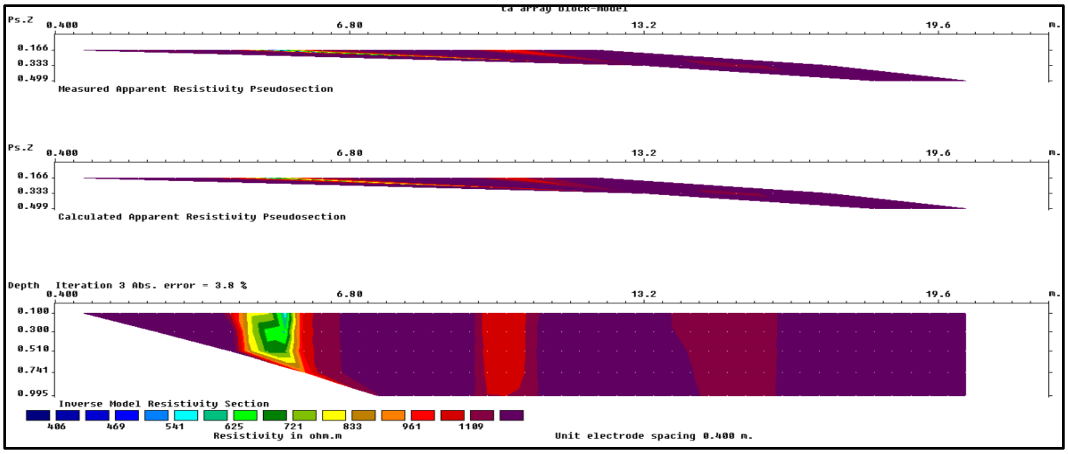

Figure 14: 2D Resistivity tomogram for profile ADM.

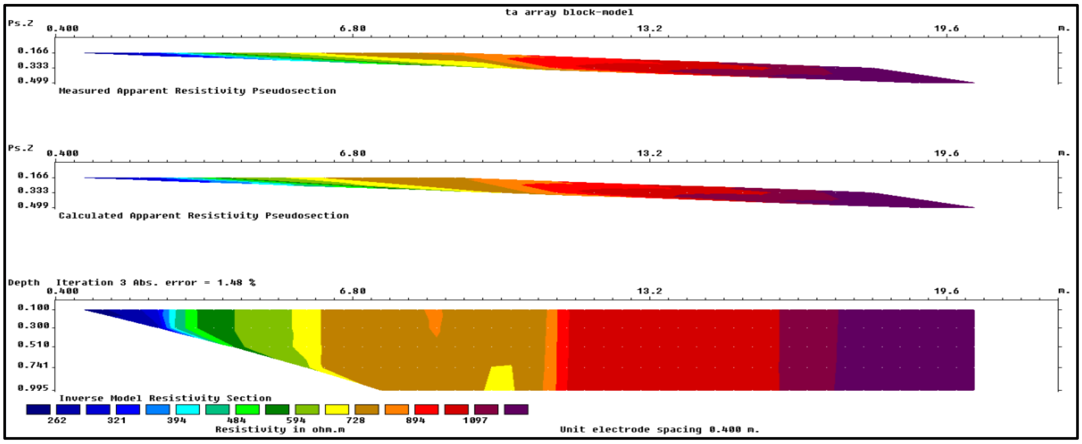

Figure 15: 2D Resistivity tomogram for profile ADM 4.

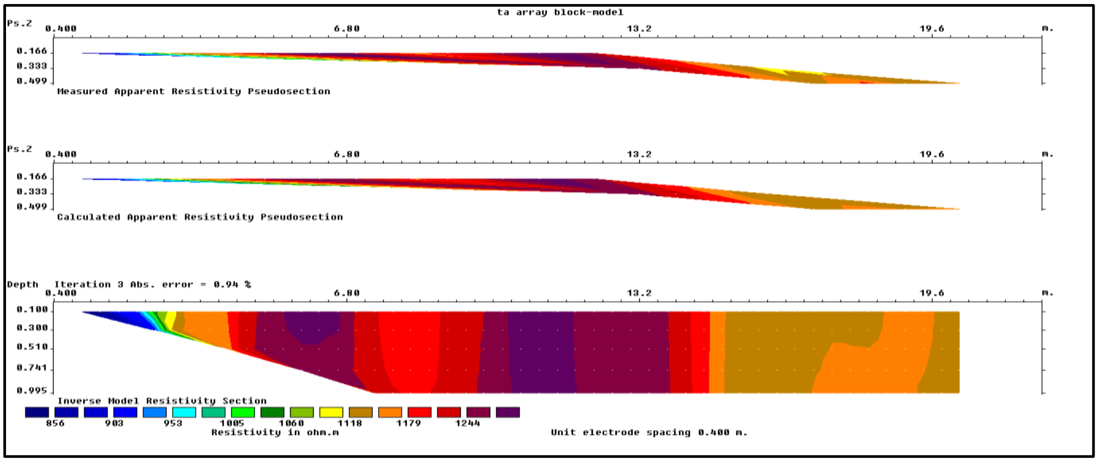

Figure 16: 2D Resistivity tomogram for profile COS 1.

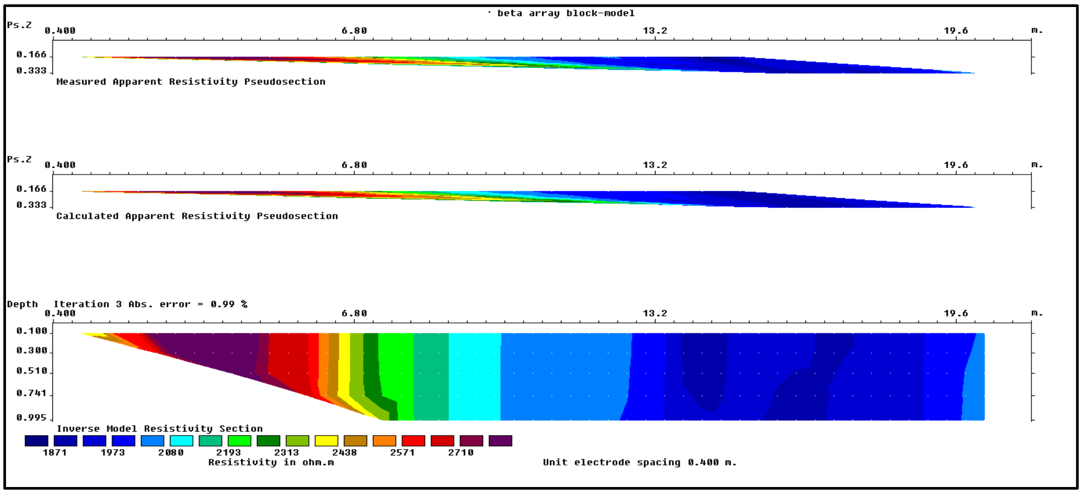

Figure 17: 2D Resistivity tomogram for profile COS 2.

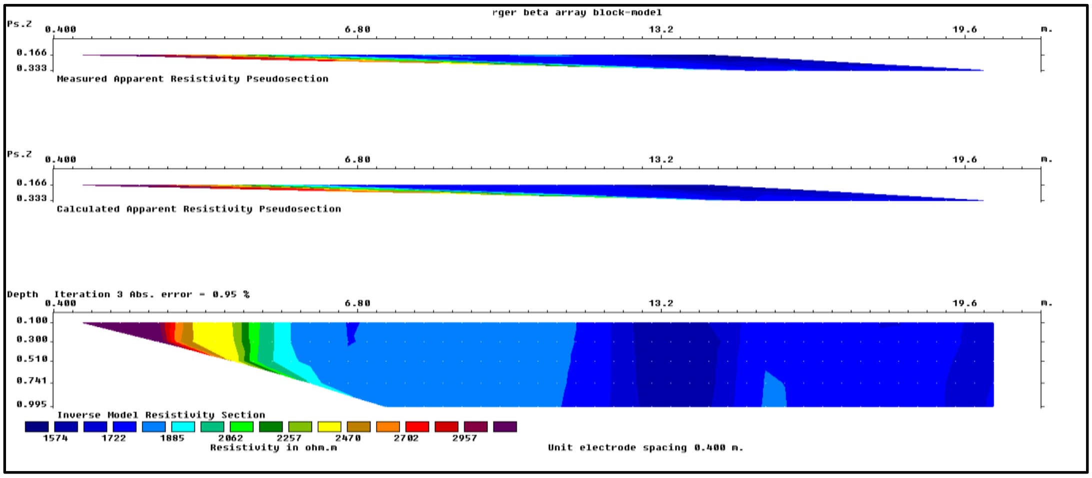

Figure 18 : 2D Resistivity tomogram for profile COS 3.

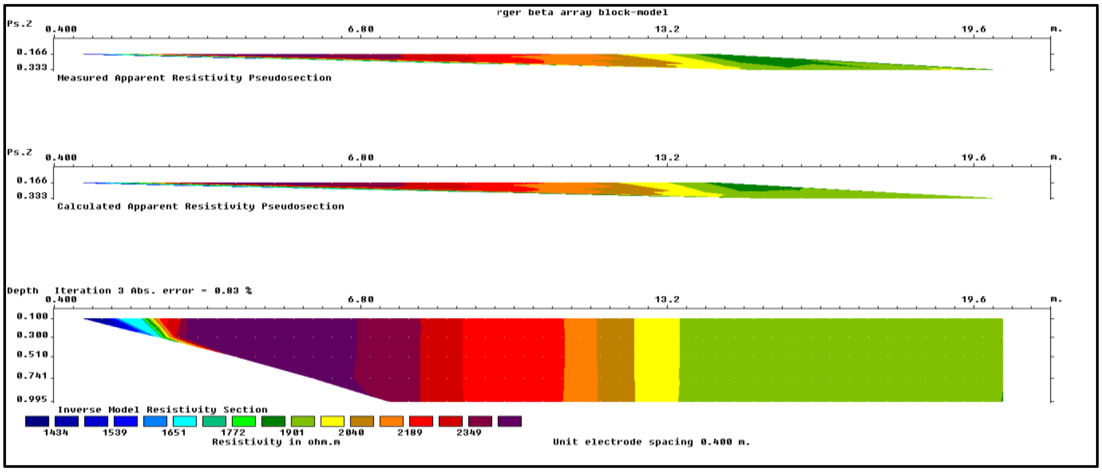

Figure 19: 2D Resistivity tomogram for profile COS 4.

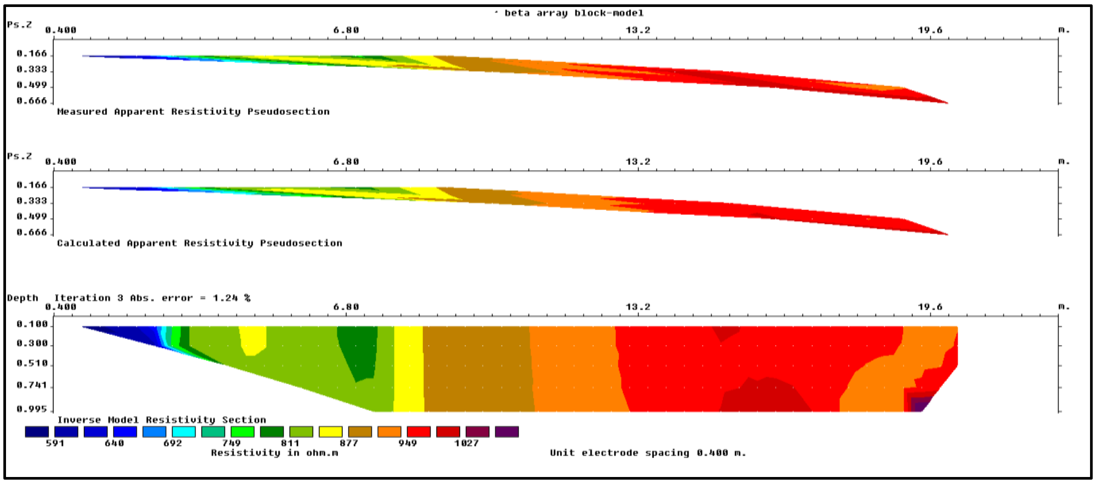

Figure 20: 2D Resistivity tomogram for profile COT 1.

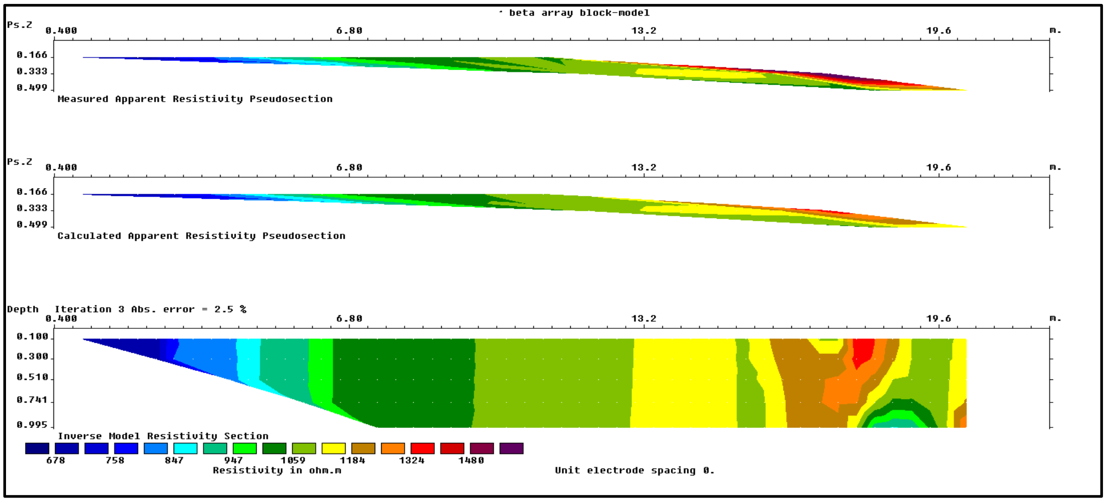

Figure 21: 2D Resistivity tomogram for profile COT 2.

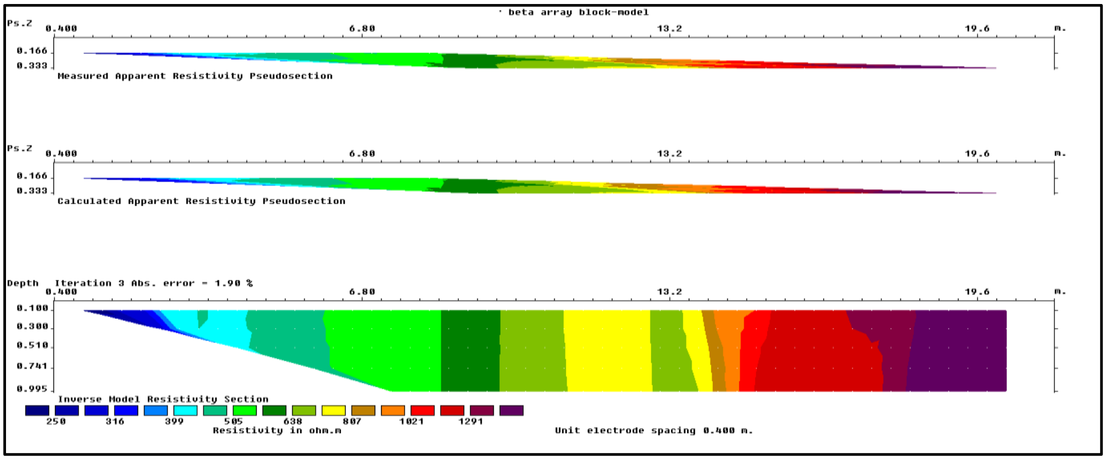

Figure 22: 2D Resistivity tomogram for profile COT 3.

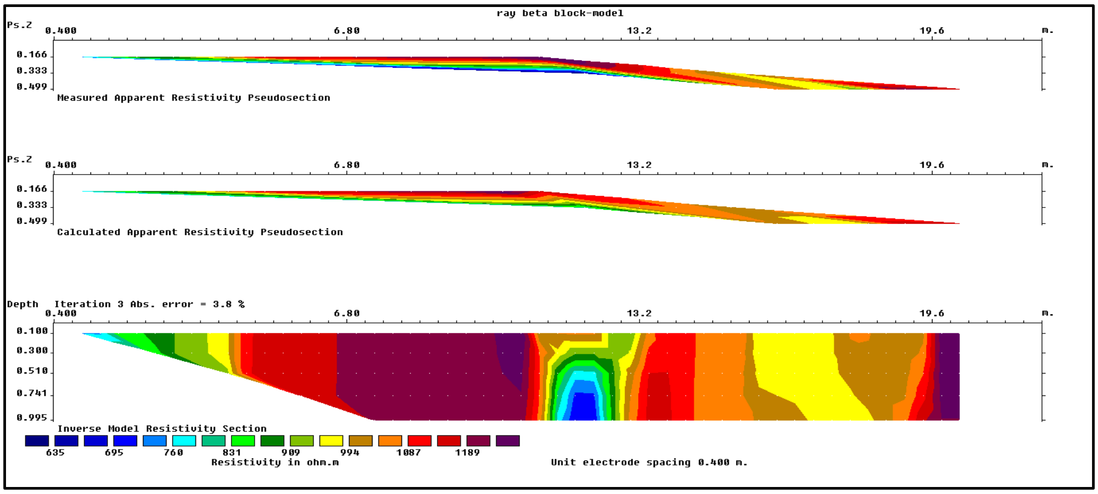

Figure 23: 2D Resistivity tomogram for profile COT 4.

Table 1: Results of inverse model resistivity and layers from ERT.

S/No.	Buildings	Inverse model resistivity (Ωm)	Soil depth range (m)	Classified soil type
1	**Library block**	**Lowest** (584 – 659)	0.9 - >2.0	Clayey-Sand
		Highest (2561 - >2877)	0.1 - 0.5	Sand
2	**Administrative block**	**Lowest** (262 – 394)	0.1 - 0.4	Clayey-Sand
		Highest (2798 - >2970)	0.3 -o.5	Sand
3	**College of science block**	**Lowest** (856 – 953)	0.1- 0.3	Clayey-Sand
		Highest (2470 - >2957)	0.1 - 0.5	Sand
4	**College of technology block**	**Lowest** (250 – 399)	0.1 - 0.5	Clayey-Sand
		Highest (1324 - >1480)	0.7 - >0.9	Sand

5. Discussion

Generally, the Delta area comprises three major subsoil types: silty sand, clayey sand and sand (from top to bottom). The results reveal that two major sub-soil types: clayey-sand and sand from top to bottom underlie the study area characterized by swampy and marshy ground conditions. Geotechnically, soils in wetland areas are generally low-bearing-capacity foundation materials with the voids saturated with water. Thus, they pose major engineering problems such as excess surface and ground water, poor drainage, high compressibility, low-bearing capacity and differential settlement among others.

The clayey-soil in FUPRE is observed to exhibit resistivity values ranging between 250 and 953Ωm which implies loss of water as at the time of investigation. Results show that there is frequent intercalation of clay within the sand in the shallow-to-deep near-surface layers at depth ranging from 0.1 to 2.0m in the study area. The seasonal volumetric changes in this clayey-soil cause it to expand multiple times by volume when saturated with water or shrink drastically when dehydrated. These changes in clayey-soils may lead to differential settlements. These differential settlements caused by the expansive clayey-soil in the area may be due to the different loads on different parts of the foundation of these buildings. The resultant uplifts vary in different parts of the buildings: the corners tend to be lifted up relative to the central portion. Such differential movements of the foundations may cause cracks, especially at the expansion joints of these buildings which foundations are located 3ft (≈1m) within this layer in the study area.

6. Conclusion

The application of Vertical Electrical Sounding (VES) and analyses by Electrical Resistivity Tomography (ERT) reveal that resistivity values vary within different soil layers around the four buildings investigated. This investigation describes the possible factors which are the most possible causes of the structural failures observed on these buildings.

Low resistivity values are observed to be prevalent in the shallow layers with intercalations of clay in sands underlying the area which mainly contributes to the expansive nature of soils. It is observed that different soil types have different degrees of expansivity with seasonal volumetric changes. Clayey-soils are observed to underlie the buildings within the top 0.1 to 2.0m, where the foundations of these buildings are located. It can therefore be concluded that the structural failures and palpable crack on the buildings in FUPRE are probably as a result of the clayey-soil type underlying the area. As part of the wetland area, it is prone to the engineering problems associated with wet soil such as: excess surface and ground water, poor drainage, high compressibility, low bearing capacity and differential settlement, among others.

7. Recommendation

Based on the findings of this study, it is recommended that proper and continuous geophysical and geotechnical investigations, maintaining standard building codes in Nigeria, be conducted prior to construction of buildings and roads in FUPRE. From the foregoing it appears that, to avoid the zone of seasonal moisture and volumetric soil changes in the study area, the base of the foundations should be at least 6ft from the ground surface (Gidigasu, 1985). Thus, foundations of buildings in FUPRE should be reinforced by piling to depths ≥ 2m (6ft) below this clayey-sand so as to withstand the seasonal volumetric expansions and shrinkages of these soils and uneven ground settlements rates underneath these foundations.

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