Investigation of Building Failure in A Typical Basement Complex Environment Using Integrated Approach – A Case Study in Ile-Ife, Nigeria

Afolabi Olaolu Oladeji Ayoola Temiloluwa Salami Babatunde Moruf* Lawal Sadiq Akorede
Department of Geology, Faculty of Science, Obafemi Awolowo University, Ile- Ife, Nigeria
*E-mail of the corresponding author: salamibm@gmail.com

Abstract
A building located within the Basement Complex of the ancient town of Ile – Ife, Osun State, Southwestern Nigeria was observed to have failed due to excessive total and differential settlement. The failure was investigated using the electrical resistivity and geotechnical methods The electrical resistivity method involved the 2-D electrical resistivity imaging (ERI) technique using the dipole-dipole array along four traverses of 30 – 60 m in lengths. The geotechnical method involved the cone penetration test (CPT) using the 2.5-ton static penetrometer machine. Quantitative and qualitative analysis of the ERI data were made using the DIPROfWIN software for the pseudo-inversion while the CPT data were interpreted for lithology using standard chart. The results show that the topsoil, about 1.0 m thick, is composed of sandy clay/clay that is characterized by cone resistance (q_c) of 0.2 – 2.0 MPa and resistivity of 75 - 200 Ωmm. The underlying clayey weathered layer, which constitute the shallow foundation soil is characterized by thickness of 4 - >10 m, q_c of 0.2 – 1.0 MPa, resistivity of 25 - 75 Ωmm and estimated consolidation settlement of 200 – 500 mm. The basal layer is the saprock/fresh bedrock characterized by q_c of > 8.0 MPa and resistivity of 100 - 1000 Ωmm. The subsoil is thus characterized by variably thick incompetent clayey weathered layer within which the shallow foundation was placed; hence the excessive total and differential settlements.
Keywords: Basement Complex, Building Failure, Electrical Resistivity Imaging, CPT, Excessive Settlement
DOI: 10.7176/JEES/14-2-01
Publication date: March 31st 2024

1. Introduction

The incessant incidence of foundation failure of structures is becoming alarming in Nigeria. This failure has been attributed to a number of factors such as inadequate information about the soil and the subsurface geological material, salinity, poor foundation design and poor building materials (Fatoba *et al.*, 2010). Building failure in the form of excessive total settlement and intolerable differential settlement or both are attributed to highly compressible foundation soils. While these types of building failure are common in sedimentary terrain underlain by recent transported soils in the form of soft clays and loose sands; they are uncommon in the Basement Complex terrain where residual soil and partially weathered rocks constitute the foundation soils.

Conventional pre and post-construction investigations of foundation soils, which usually involve shell and auger exploratory borings along with cone penetration tests, are generally effective in area underlain by transported soils that are usual characterized by fairly uniform stratification within space of hundreds of meter. However, this technique may not be effective in the Basement Complex terrain characterized by highly heterogeneous subsoil sequence within short distance. In such terrain, integration of geophysical methods into conventional geotechnical investigation program have been found to be useful (Olorunfemi and Mesida, 1987; Adepelumi and Olorunfemi, 2000b; Olorunfemi *et al.*, 2000b; Akintorinwa *et al.*, 2011, and Salami *et al.*, 2012).

A building located within the Basement Complex of the ancient town of Ile – Ife, Southwestern Nigeria was observed to have failed due to excessive total settlement. The aim of this study was to investigate the cause of the failure with the objective of evaluating the competence of subsurface sequence in the vicinity of the building as foundation elements. The Electrical Resistivity method involving the Vertical Electrical Sounding technique using the Schlumberger configuration and the Resistivity Imaging method using the dipole-dipole configuration as well as Cone Penetration Tests (CPT) were used for the investigation. The study area lies between latitudes 7^{o}29'37.3''N – 7^{o}29'38.3''N and longitudes 4^{o}31'39.3''E – 4^{o}31'40''E (Figure 1).

2. Geology of the Study Area

The study area is part of the Ife-Ilesa schist belt which consists of three major units: the Ilesa amphibolite Complex which occurs as lenticular bodies, the Ilesa metaclastics made up of sheared biotite schists, and the Effon quartzitic sequence which occurs as massive quartzite, schistose quartzite and quartz schist. The study area is underlain by pegmatized schist (Figure 2) which has been severely weathered. The pegmatized schist is generally dark grey in colour with texture ranging from medium to coarse grain. Its mineralogical composition includes biotite, quartz, muscovite, plagioclase and potassium feldspars which makes it highly susceptible to weathering.

3. Methodology

The underlisted methods were employed in the cause of this study.

3.1 Geophysical Investigation

The geophysical investigation employed the Electrical Resistivity method adopting the 2-D Electrical Resistivity Imaging (ERI) technique using the dipole-dipole array along four traverses (TR1 – 4) of 30 – 60 m lengths that were positioned along the perimeter of the building. Electrode spacing a = 2 m and dipole spacing n = 1 to 5. Quantitative and qualitative analysis were made using the DIPROfWIN software for the pseudo-inversion. The data acquisition was done using the ABEM 300C Terrameter.

3.2 Geotechnical Investigation

The Cone Penetration Test (CPT) was used to determine the strength of the subsurface sequence based on the measured values of cone penetration resistance (q_c) at various any depths. The CPT was performed at three positions within the study area using a 2.5 ton Dutch cone penetration machine. The test was carried out by securing the winch frame to the ground by means of anchors. These anchors provided the necessary power to push the cone into the ground. The cone and the rod (1 m) were pushed together into the ground with the cone pushed ahead of the rod at a uniform rate of about 2 cm/s. The resistances to penetration of the cone, registered on the pressure gauge connected to the pressure capsule, were recorded at depth intervals of 0.25 m from ground surface to the points of refusal i.e. points where the machine anchor legs were lifted or pulled out of the subsurface. The procedure described above was then repeated for subsequent location tests.

The CPT data were processed by plotting the cone resistances against depth at each location point using the Microsoft Excel software. The layer sequences were interpreted from the variation of the values of the cone resistance with depth. On the basis of the expected resistance contrast between the various layers, inflection points of the generated penetrometer curves were interpreted as the interface between the different lithologies.

4. Results and Discussion

4.1 Electrical Resistivity Survey

The 2-D resistivity structures along the four traverses depict the subsurface resistivity distributions (Figure 3).

Traverse 1: The resistivity structure (Fig. 3a) shows subsoil sequence along the Northwestern flank of the site as having resistivity values varying from 34 Ω m to 330 Ωm. The topsoil with predominantly yellow colour, occurring to about 1.0 m depth, has resistivity values that generally vary from 102 – 167 Ωm, with minor portion in green colour having low resistivity values of 35 – 67 Ωm. This portrays heterogeneous soils composed mainly of sandy clay and minor clay. The underlying layer in predominantly green colour, occurring from about 1.0 to 4.0 m depth, is characterized by resistivity values ranging from 48 to 95 Ωm, which is typical of sandy clayey weathered layer. The basal layer in reddish colour, characterized by resistivity values of 110 – 330 Ωm, is regarded as the saprock/fresh bedrock. Depth to the fresh bedrock varies from about 2 m at the origin in the NW about at the terminal 4 m in the SE.

Traverse 2: The resistivity structure (Fig. 3b) shows that the subsoil sequence along the Northeastern flank of the site has resistivity values varying from 28 Ωm to 986 Ωm. The topsoil with bluish green colour, occurring to about 1.0 m depth, has resistivity values that generally vary from 51 – 107 Ωm, which is regarded as sandy clayey material. The underlying layer in blue/green colour, occurring from about 1.0 to 3.0 m depth, is predominantly chracterized by resistivity values of 28 – 55 Ωm, hence regarded as clayey weathered layer. The third layer, ocurring from 3.0 – 4.5 m in yellow and green colours with resistivity values of 80 – 120 Ωm is regarded as clayey sand weathered layer The basal layer in red/purple colour, characterized by resistivity values of 122 - 986 Ωm, is regarded as the saprock/fresh bedrock. Depth to the fresh bedrock varies from about 4 m at origin in the NE to about 15 m at the terminal in the SW.

Traverse 3: The resistivity structure (Fig. 3c) depicts the subsoil sequence along the Southeastern flank of the site as having resistivity values of 27 Ωm to 271 Ωm. The topsoil in yellow/green colour, occurring to about 1.0 m depth, has resistivity values that generally vary from 42 – 115 Ωm, thus regarded as residual soils composed mainly of clay and sandy clay. The underlying layer in blue/green colour, occurring from about 1.0 to 5.0 m depth, with resistivity values of 22 – 75 Ωm is interpreted as clayey weathered layer. The basal layer in red/purple colour, characterized by resistivity values of 90 – 271 Ωm, is regarded as the saprock/fresh bedrock. Depth to the fresh bedrock varies from about 6.0 m in the NE origin to over 10 m in the SW end.

Traverse 4: The resistivity structure (Fig. 3d) shows that the subsoil sequence along the southwestern flank of the site is characterized by low resistivity varying from 6.0-138 Ωm. The topsoil in green/yellow colour, occurring to 1.0 – 2.0m depth, has resistivity values that generally vary from 48 – 138 Ωm, hence interpreted as residual soils composed mainly of clay and sandy clay. The underlying layer in blue/green colour, occurring to about 4.0 m depth, with resistivity values of 21 – 62 Ωm is interpreted as clayey weathered layer. The underlying layer, in predominantly blue colour, characterized by low resistivity values of 6.0 – 43 Ωm is considered to be soft clayey material. The fresh bedrock was not delineated beneath this traverse.

4.2 Geotechnical Survey

Results of the cone penetration tests are presented as plots of cone resistance (q_c) against depth (Figure 4). For the purpose of lithological interpretation, the q_c values were correlated with Schertmann chart (1978). The friction ratio, which could not be measured with 2.5 ton penetrometer machine, is taken to vary from 2-5 based on classification of Look (2007).

Analysis of the results show that from ground surface to depth of 2.5 m, CPT 1 and CPT 3 are generally characterized by low q_c of 0.196 MPa (2.0 kgf/cm^2) indicating incompetent subsoil composed of soft clays. Corresponding section beneath CPT 2 to 2.0 m is characterized by relatively higher q_c of 0.196 – 1.96 MPa (2.0 to 20 kgf/cm^2), which indicates fairly competent subsoil composed of sandy/silty clays or stiff clay.

From 2.25/2.75 m to 3.5 m, the q_c values for the test points generally varies from 1.47 -7.10 MPa (15 to 72 kgf/cm^2), which is regarded as moderately competent subsoil composed of sandy and silty clays. The last layer penetrated by the cone, from 3.5-4.0 m has q_c that generally varies from 8.82 -10.5 MPa (90 - 107 kgf/cm^2), which is regarded as competent subsoil saprock composed of coarse-grained clayey sand.

5. Synthesis of Results

The composite resistivity structure of the site was generated by integration of the 2-D along Traverses 1 – 4, with the aid of Surfer 11 software, and was used to determine the generalized resistivity of the subsoils beneath the failed building at different depths.

The results (Figs. 5 - 8) show that, beneath the investigated building, from the ground surface to 1.0 m depth, the subsoil is chracterized by resistivity values varying from 75 - 200 Ωmm and q_c varying from 0.196 to 1.96 MPa. The layer is thus regarded as dry portion of clays and sandy/silty clays delineated by the CPT. The underlying subsoil to depth of 4 m is chracterized by resistivity values varying from 25 -75 Ωm, with resistivity values decreasing with depth. This horizon is considered to be clayey weathered layer occurring as mottled zone of saprolite. The horizon corresponds to the soft clay and stiff silty clay delineated by the CPT to depth of 2.5 m.

At depth of 4 to 7 m, the subsoil is characterized predominantly by resistivity values of 100 to 500 Ωm, which is typical of pallid zone of saprolite and corresponds to the sandy and silty clays delineated by the CPT. The basal layer at depth of 7 to 10 m characterized mainly by resistivity values of 100 - 1000 Ωm portrays occurrence of saprock and fresh bedrock. The southwestern portion is however characterized by subsoil with low resistivity values to depth beyond 10 m. This suggests occurrence of buried river channel in that part of the study area.

The clayey subsoil constitutes the horizon for shallow foundation. Undrained shear strength (Cu) parameters of the horizon were estimated from q_c values (kPa) based on Look (2007) relationship:

$$C_u = \frac{q_c}{N_k}$$

[q_c values are in kPa; N_k = cone factor = 18] (1)

The results shows that the horizon is generally characterized by low undrained shear of 11 kPa except in the northwestern portion of the site that has undrained shear of 54 kPa.

In addition, the horizon has thickness varying from 4 m in the NE to >10 m in the SW portiom of the site. Consolidation settlement (S_c) of the horizon was estimated from constrained modulus (M), which is inverse of coefficient of volume change (M_v); hence:

$$S_c = \frac{1}{M}.H.\Delta\sigma \quad (2)$$

Also, M was estimated from q_c based on relationship:

$$M = \alpha_m . q_c \quad (3)$$

For $q_c < 0.7$ while α_m range is $3 < \alpha_m < 8$ (Sanglerat, 1972). The lower value of $\alpha_m = 3.0$ was adopted for this study due to the low q_c value of 0.2 MPa. Also, the failed building has two floors (ground floor and first floor), hence loading intensity of 30 kPa was adopted. The estimated consolidation settlement varied from 200 mm in the NE section to 510 mm in the SE section of the building.

6. Conclusion

The subsoil at the study area is characterized by variably thick incompetent clayey horizon within which the shallow foundation was placed; hence the excessive total and differential settlement.

References

Adepelumi A.A. and Olorunfemi M.O., (2000), "Engineering Geological and Geophysical Investigation of the Reclaimed Lekki Peninsula, Lagos, South-west Nigeria", *Bulletin of Engineering Geology and the Environment* **58**, 125-132.

Adepelumi A.A., Olorunfemi M.O., Falebita D.E. and Bayowa O.G., (2009), "Structural Mapping of Coastal Plain Sands using Engineering Geophysical Technique: Lagos Nigeria Case Study", *Natural Science*, **1**(1), 2-9.

Brook M., Keary P. and Hill I., (2002), "An Introduction to Geophysical Exploration", *Blackwell Scientific Publication*. Oxford, U.K, 198 – 269.

Ibitoye F.P., (2013), "Application of Geophysical Methods to Building Foundation Studies", *International Journal of Geosciences* **4**, 1256-1266.

Look, B. G. (2007), "Handbook of Geotechnical Investigation and Design Tables". *Taylor and Francis*, London, 356.

Meshida, E.A., (1987), "The Relationship between the Geology and the laterite engineering soil in the Northern Environs of Akure, Nigeria", *Bulletin of the International Association of Engineering Geology* **35**, 65-68.

Olorode D.O, Adedayo A.S. and Akintunde A.O., (2016), "Application of Geotechnical and Geophysical Methods to Investigate Tilt Buildings at Lagos State, Nigeria", *Journal of Applied Geology and Geophysics* **4**(5) Ver. II, 21- 23.

Olorunfemi M.O. and Meshida E.A., (1987), "Engineering Geophysics and Its Application in Site Investigations (case study from Ile-Ife area)". *The Nigerian Engineer*, **22**(2), 54-57.

Oyedele K.F., Oladele S. and Adedoyin O., (2011), "Application of Geophysical and Geotechnical Methods to Site Characterization for Construction Purposes at Ikoyi, Lagos, Nigeria", *Journal of Earth Sciences and Geotechnical Engineering*, **1**(1), 87-100.

Sanglerat G., (1972), "The Penetration and Soil Exploration", *Development in Geotechnical Engineering*, Elsevier Scientific Publishing, New York, 52-80.

Telford W.M., Geldart, L.P., Sheriff R.E. and Keys D.A., (1990), "Applied Geophysics (Second Edition)", Cambridge University Press, 344-536.

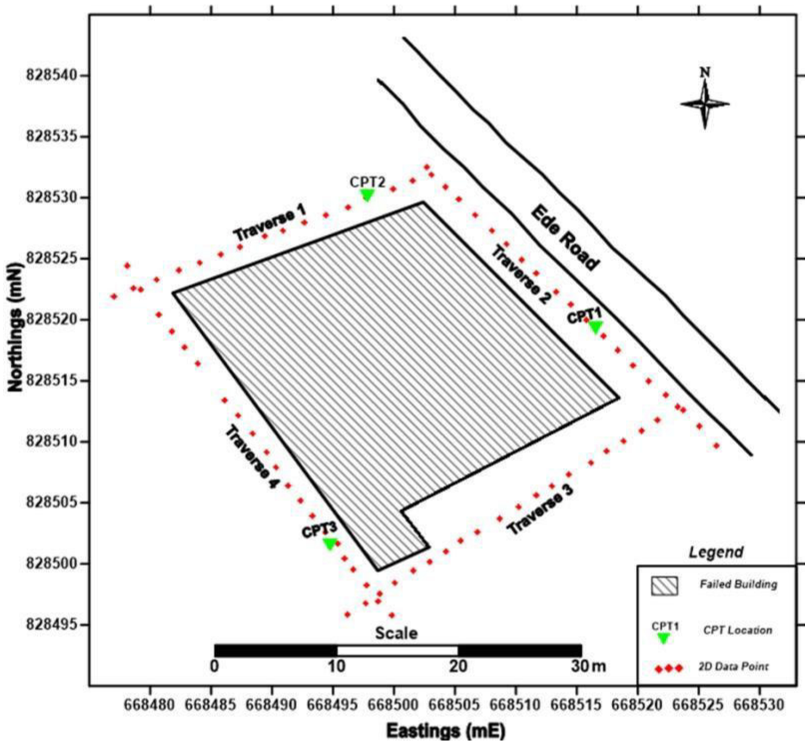

Figure 1. Map of the Study Area Showing the Test Positions

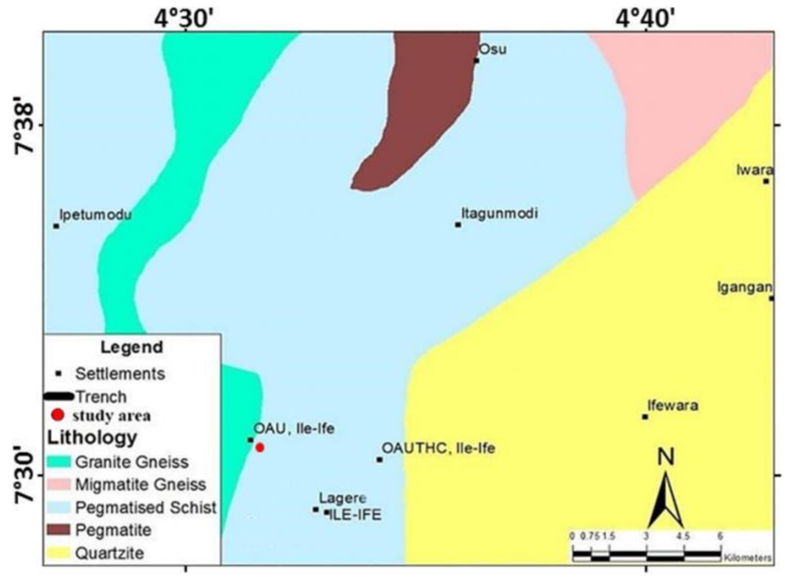

Figure 2. Geological Map of the Study Area and its Environs (Olorunfemi *et al.*, 2015)

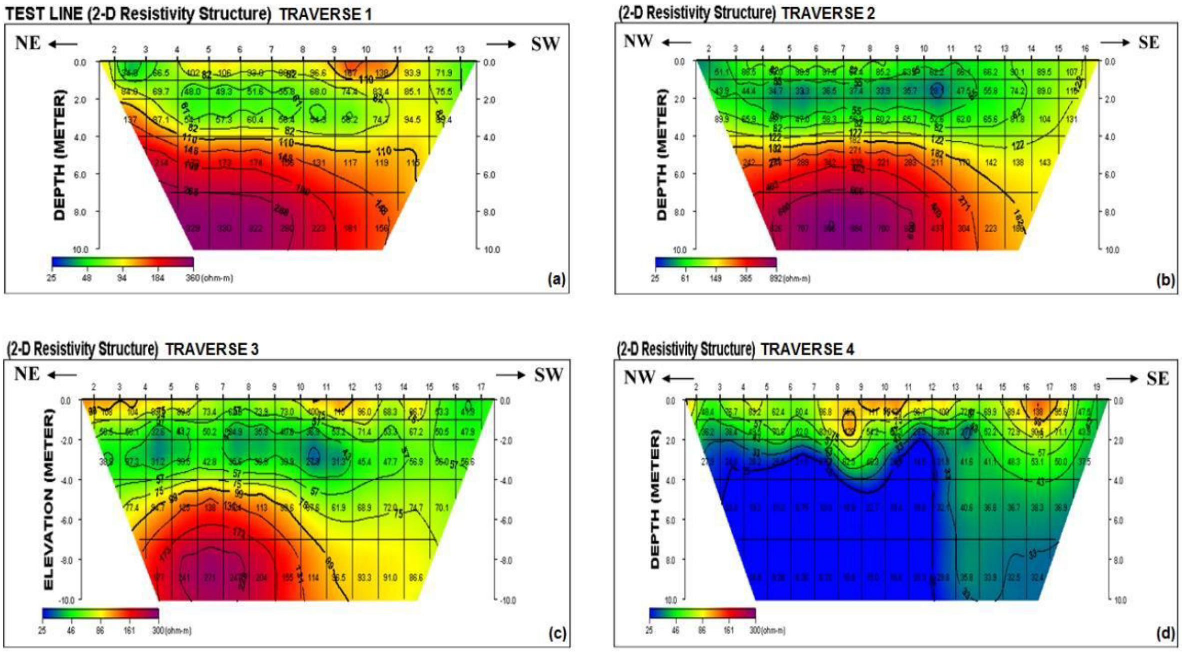

Figure 3. 2-D Resistivity Structure along ERI (a) Traverse 1 (b) Traverse 2 (c) Traverse 3 (d) Traverse 4

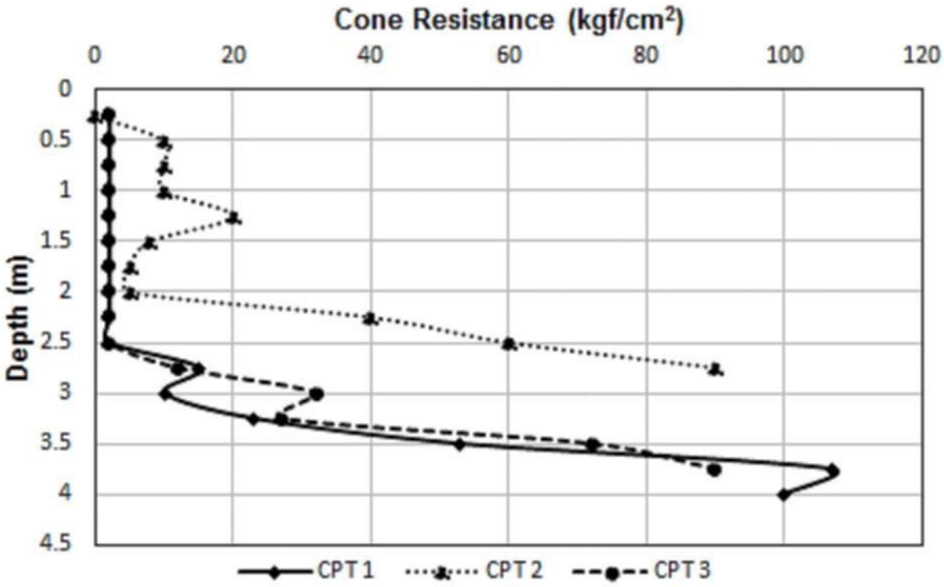

Figure 4. Cone Resistance Plots for CPT 1, 2 and 3

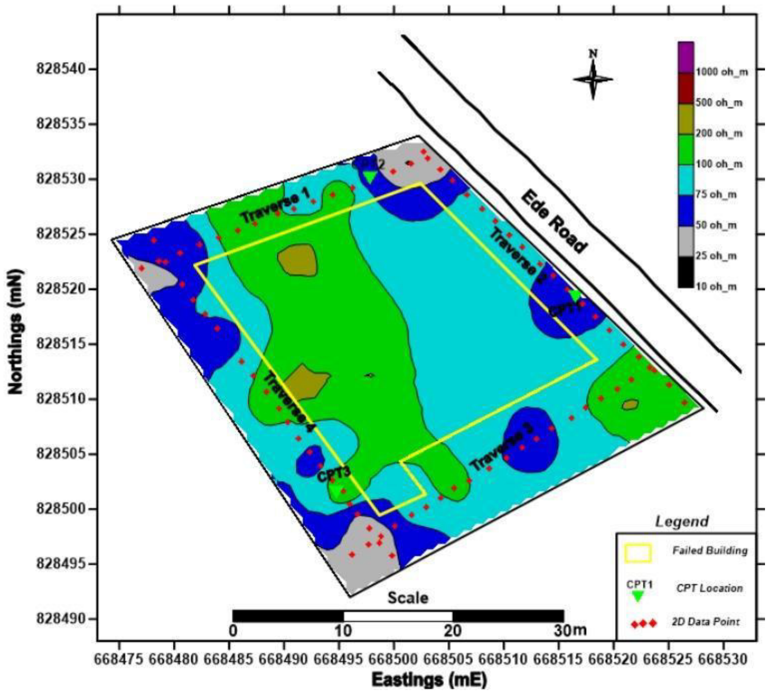

Figure 5. Resistivity Depth Slice at 0 – 1.0 m

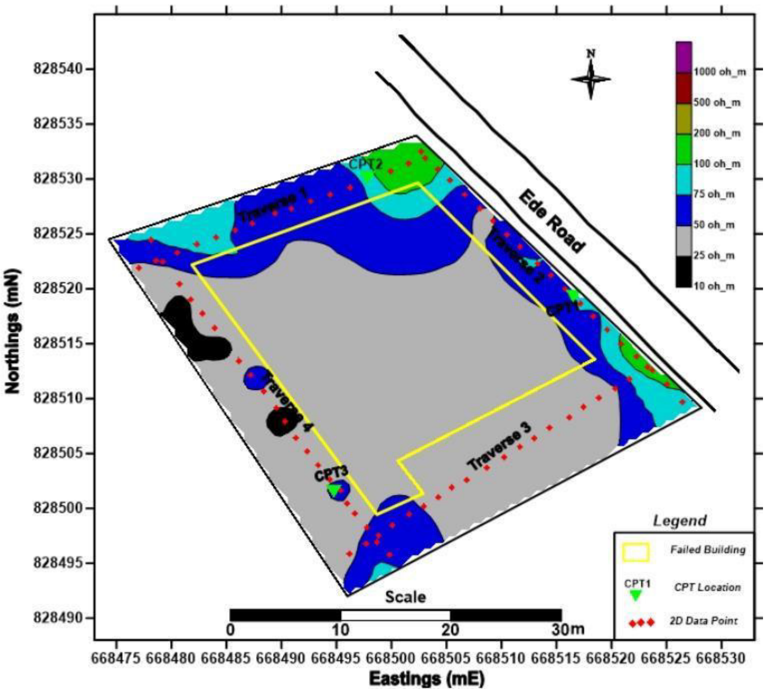

Figure 6. Resistivity Depth Slice at 2.0 – 4.0 m

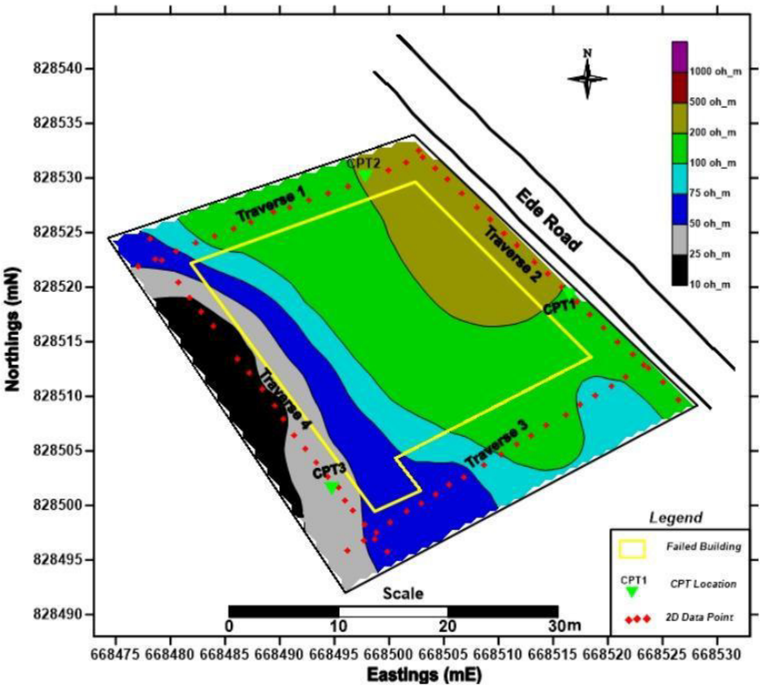

Figure 7. Resistivity Depth Slice at 4.0 – 7.0 m

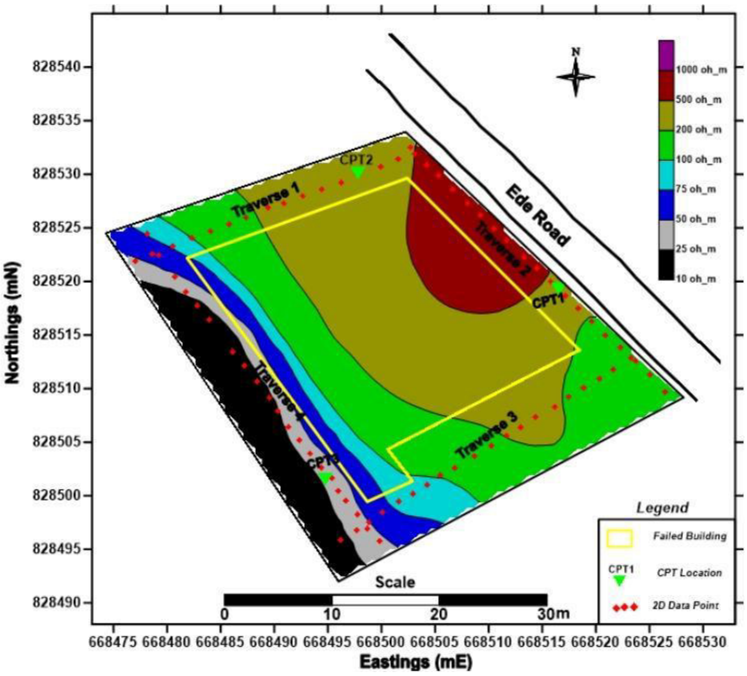

Figure 8. Resistivity Depth Slice at 7.0 – 10.0 m