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Geophysical and Geotechnical Examination of Structural Failure in Federal University Otuoke, Nigeria

Ibe, S.O. and Anekwe, U. L.

Department of Physics, Federal University Otuoke, Nigeria

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Abstract

The cause of foundation based structueral failure of some buildings in the premises of Federal University Otuoke, Nigeria was investigated using electrical imaging technique and geotechnical test involving moisture content, bulk density, specific gravity, free swell and texture determinations. The apparent resistivity data collected with ABEM SAS 300C Terrameter along three profiles, respectively laid in the vicinity of the affected buildings were processed using RES2DINV Software to produce the 2-D electrical resistivity tomograms. The results showed that the electrical resistivities of the subsoil at shallow depths underlying the buildings in the areas range from 2 to 1100 Ω and this range encompasses the range for Sandy Silty Clay, Coarse Sand and clay respectively. The geotechnical test showed that the soils in the area are predominantly Sandy Silty Clay, Clay and Coarse Sand, fine aggregates, probably sandfill. The ranges of the moisture content (4.40 – 36.25%), bulk density (1.11 – 2.08 gcm^{-3}), specific gravity (1.69 – 2.71) and free swell (0.0 – 106.3%) of the soil layers directly underlying the buildings suggest that the structural failures are most likely initiated by differential settlement caused by significant variation laterally in the compaction of the soils and clay swelling. Therefore, to minimise structural failure in the university and its environs, building engineers in the area should ensure that each building is directly underlain laterally by the same type of soil having no significant difference in compaction.

*Corresponding Author; Ibe S.O.: stphnibe@yahoo.com

Introduction

In many parts of the world there have been records of lost of lives and property resulting from structural failure of buildings, bridges and dams. Collapse in Buildings could be total or partial failure of one or more components of a building leading to the inability of the building to perform its principal function of safety and stability.Olagunju *et al.*(2013) had observed that collapse of buildings is a universal problem that has eaten deeply into the fabrics of the construction industry, of which very little has been done to curb the menace. Records of structural failure of buildings are very common in Western Canada, Coloorado, Texas and Wyoming, India, Israel, South Africa and to some extent South Austrlia, Califonia, Utah, Nebraska and South Dakota. Nigeria like many other countries has witnessed collapse of building at alarming rate, especially, in urban cities of of Abuja, Lagos, Enugu, Port Harcourt, Ibadan, Kaduna and Uyo (Chinwokwu, 2000; Famoroti, 2006; Ayodeji, 2011; Olagunju *et al.*, 2013; Okechukwu, 2017).

The desired satisfaction, comfort and safety of a building tend to be threatened when the building failed to perform any of its principal functions of satisfaction, safety and stability (Olagunju *et al.*, 2013). Building failure may be as a result of a total or partial failure of one or more components of a building structure. It is a defect or imperfection, deficiency or fault in a building element or component and may also be as a result of omission of performance. The degree of building failure can therefore be related to the extent or degree of deviation of a building from the "as – built" state which in most cases represent the acceptable standard within the neighbourhood, locality, state or country (Ikpo, 1998).

Most structural failures are caused by swelling clays and the foundation of any structure is meant to transfer the load of the structure to the ground without causing the ground to respond to uneven and excessive movement (Blyth and Freitas, 1988). Hence, the knowledge of the probable cause of rampant failure of building foundations due to

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subsurface movements giving rise to cracks or structural differential settlements is now of great concern to Geoscientists. This knowledge equips the Geoscientists to distinguish between a continuing movement, which is often more likely to be a problem and those of a single events, which may not require repair depending on the extent of damage (Egwuonwu, 2008).

There are several types of foundation cracks (Edgar, 1980, Donald and Cohen, 1998 and Egwuonwu, 2008) but the major ones include: (i) Vertical Foundation Cracks which are cracks that are fully or partially parallel to the orientation of the building walls are usually caused by either poor soil or conditions under the footer which supports the concrete block walls, that is, the condition which may be either poorly compacted dirt under the footer or for excavated area, soil that is not stronger than the weight of the building at the level of excavation (ii) Diagonal Foundation Cracks which are cracks that take diagonal or steep pattern on the wall of buildings are usually caused by settlement, expansive clay soil, frost or close range existence of shrubs or trees and (iii) Horizontal Foundation Cracks which are cracks that are fully or partially normal to the walls of builbings; usually originate from the dirts which rest against the foundation of a building, takes place when the back fill pushes against the foundation wall.

Horizontal Foundation Cracks pose more treat to buildings than Vertical and Diagonal Foundation Cracks while Vertical Foundation Cracks pose least treat to buildings than others.

Egwuonwu (2008) classified the causes of foundation based structural failure of buildings as (i) Effect of Foundation Types which arises due to material or the type of material used for foundation and includes Stone Foundation Defect, Brick Foundation Defect, Masonry Block Foundation, Wood Foundation and Shallow Foundation (ii) Soil and Rock Problems and (iii) Effect of Tree growth on building stability.

These effects translate to foundation failure of buildings due to frost, water, vehicles which are driven close to walls (Egwuonwu, 2008), burnt bricks, moisture content variation leading to volume expansion and shrinkage of clay soil (Lambe, 1958b; Graymount, 2006), concrete shrinkage or compression stress, fractured and jointed rocks (Lew, 1973), trees growing or removed close to existing buildings (Samuel and Cheney, 1974).

Builders have various specialised solutions for different types of foundation cracks and problems. There is no single solution to all types of building foundation failures. Egwuonwu (2008) observed that the actual cause of foundation failure needs to be identified correctly so that the proper solution is employed. Geophysicists, Geologist and Building Engineering Inspectors make a reasonable confident guess about the cause of foundation movement; hence also can make the estimate of the type and rate of continuation of the changes. Geoscientists in Nigeria have attributed the reoccurences of damages on structure, shortly after construction or reconstruction, to works that were not based on studies (Ibe and Egwuonwu, 2013). Geophysical and Geotechnical studies that are suppose to preceed building constructions are not usually done before the actual construction.

Some buildings in Federal University Otuoke, Bayelsa State, Nigeria have recently developed some foundation based structutral defects of various degrees. The observed foundation structutral defects affecting the buildings are predominantly gaps between the walls and floors of the buildings (Figures 1), cracks in the walls (Figures 2) and floor creaking (Figures 3), sometimes, accompanied with popping sounds.

Fig. 1: Gap Between the Wall and Floor of a Building in the University

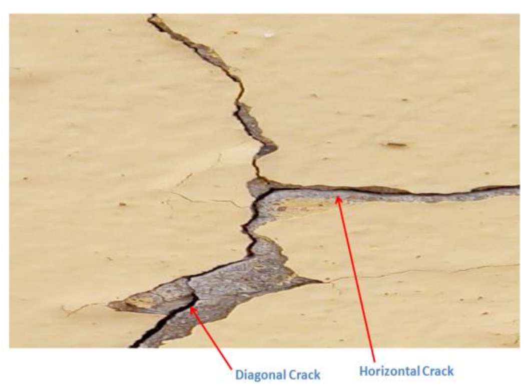

Fig. 2: Diagonal and Horizontal Cracks on the Wall of a Laboratory in the University

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Fig. 3: Floor Creaking in a Classroom in the University

This study is aimed at delineating the subsurface features, at foundation and shallow depths, responsible for the foundation based structutral defects on the affected buildings. Geophysical investigations involving Resistivity Imaging, and Geotechnical investigations involving Moisture Content, Bulk Density, Specific Gravity, Free Swell and Texture tests of the soils samples directly underlying the affected buildings' foundations were used for the study.

The Study Area and Its Geology

This study targeted some buildings affected by foundation based structutral defects, within the premises of Federal University Otuoke, Bayelsa State, Nigeria (Figure 4). Federal University Otuoke is located in Otuoke town, Ogbia Local Government Area of Bayelsa State. Bayelsa State is located in the coastal region of South-south Nigeria within the Niger Delta region of Nigeria.

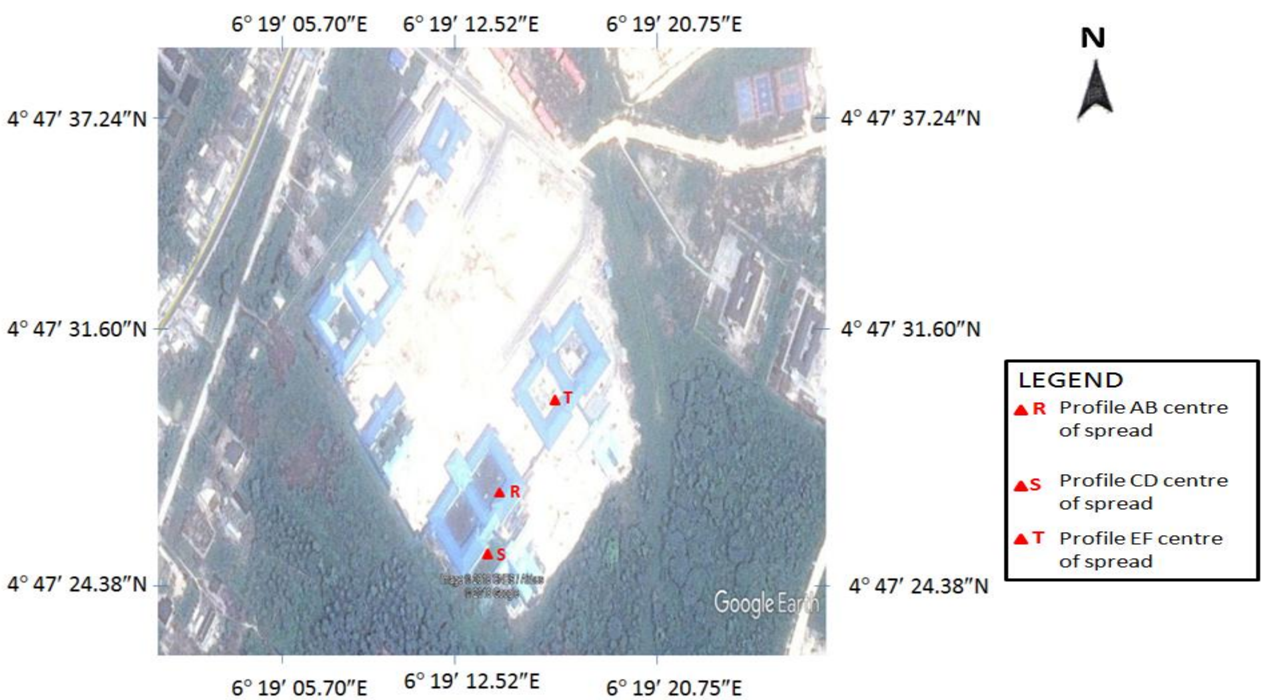

Fig. 4: Map of the Study Area Showing Centre of Spread of Each Profile (Adopted from Google Earth)

Our present knowledge of the geology of the Niger Delta is derived from the works of Reyment (1965), Short and Stauble (1967), Murat (1970), Merki (1970) as well as the exploration activities of the oil and gas companies in Nigeria. The Niger Delta Basin, occupying a total area of about 300,000 km^2, is an extensional rift basin located in the Niger Delta and the Gulf of Guinea on the passive continental margin near the western coast of Nigeria (Tuttle *et al.*, 1999) and partly extends to Cameroon, Equatorial Guinea and São Tomé and Príncipe. Oceanic basement rock of pre-rift time period and basaltic in composition is the oldest rock in the basin. Also closer to the coast is the Precambrian continental basement.

The Niger Delta Basin was formed by a failed rift junction during separation of the South American plate and the African plate, as well as the opening of the South Atlantic. That is, the Basin was formed during the Tertiary period as a result of the interplay between subsidence and deposition arising from a succession of transgressions and regressions of the area. According to Tuttle *et al.* (1999), there is a section of rock in this basin from the middle to late cretaceous that is believed to be composed of sediments from a tide dominated coastline comprising several layers of shales. The sediment fill of the basin has a depth between 9 – 12 km (Fatoke, 2010) and it is composed of several different geologic formations that indicate how this basin was formed, as well as the regional and large scale tectonics of the area.

The formation of the present Niger Delta started during early Paleocene as a result of the built up of fine grained sediments eroded and transported to the area by the River Niger and its tributaries. The regional geology of the Niger Delta consists of three lithostratigraphic units comprising a lower shaly Akata Formation, an intervening unit of alternating sandstone and shale named the Agbada Formation and an upper sandy Benin Formation. These Formations are underlain by various types of Quaternary deposits. According to Osakuni and Abam (2004), these Quaternary sediments are largely alluvial and hydromorphic soils and lacustrine sediments of Pleistocene age.

The annual rainfall in the Niger Delta is high and varies from 500 mm per annum at the coasts, to about 300 mm at the northern part of the delta (Etu-Efeotor and Odigi, 1983). Evapo-ranspiration is 1000 mm, leaving an effective rainfall of 2000 mm (Nwankwoala and Ngah 2014). Of this effective rainfall, 37% or 750 mm is known to recharge the subsurface aquifers while the remaining 1250 mm flows directly into the streams. This recharge which is 75% of the total precipitation is on the high side of the range commonly reported for unconsolidated sediments (Vecchioli and Miller, 1973). This ensures that the region is adequately supplied with water. Besides, rain may fall at any time of the year, even during the peak of the dry season, further ensuring an all year round water input into the region. Basically, the Niger Delta water resources are drawn from the Eastern littoral hydrological and the Niger South hydrological zones (Nwankwoala and Ngah, 2014).

Materials and Methods

Electrical resistivity tomography data were collected with ABEM SAS 300C Terrameter along profiles, AB with centre of spread R, CD with centre of spread S and EF with centre of spread T (Figure 4), each laid at available spaces closest to the affected parts of the buildings respectively having structural failures. The maximum length for each profile is 60.0 m and this was suitable for the depth of probe (depths in the immediate vicinity of the buildings' foundation) and for the spaces available (to minimize electrode offsets) in the vicinity of the affected building in the developed area of the University premises. The processing of the apparent resistivity measurements was carried out using RES2DINV Software to produce the 2-D electrical resistivity tomograms.

Using hand auger, subsoil samples for laboratory test were collected at possible locations closest to the affected parts of the buildings having structural failures at depths (1.5 m in profile AB and CD and 0.5 m in profile EF) depending on the type of defects. Samples were also similarly collected at some locations where there are observed anomalies in the interpreted resistivity tomography. Some physical properties of the soil samples were examined to obtain the parameters used as indices for assessing building stability. Preliminary laboratory investigations were carried out on the soil samples to delineate the subsurface structures favourable for structural failures. Hence the soil samples were subjected to lithological descriptions and laboratory testing programmes comprising (i) Moisture content determination, (ii) Bulk density determination, (iii) Specific gravity determination and (iv) Free Swell Test.

The results obtained from the interpreted electrical resistivity tomography data and the geotechnical laboratory test were used to infer the possible causes of the structural failure in some buildings in Federal University Otuoke.

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Results and Discussion

The interpreted results of the 2-D electrical resistivity tomography data are presented in Figures 5 – 7. The soil stratigraphy at shallow depth delineated by the electrical resistivity data suggests that the subsoil in the study area is laterally heterogeneous in composition and/or compaction. The results have shown that the electrical resistivities of the subsoil at shallow depths in the areas range from about 2 Ω to 950 Ω (Figure 5), 25 Ω to 1100 Ω (Figure 6) and 2 Ω to 120 Ω (Figure 7). These ranges of the electrical resistivities encompass the ranges for clay (1 – 100 Ω), Sandy, Silty Clay (100 – 200 Ω) and Coarse Sand (800 – 1800 Ω).

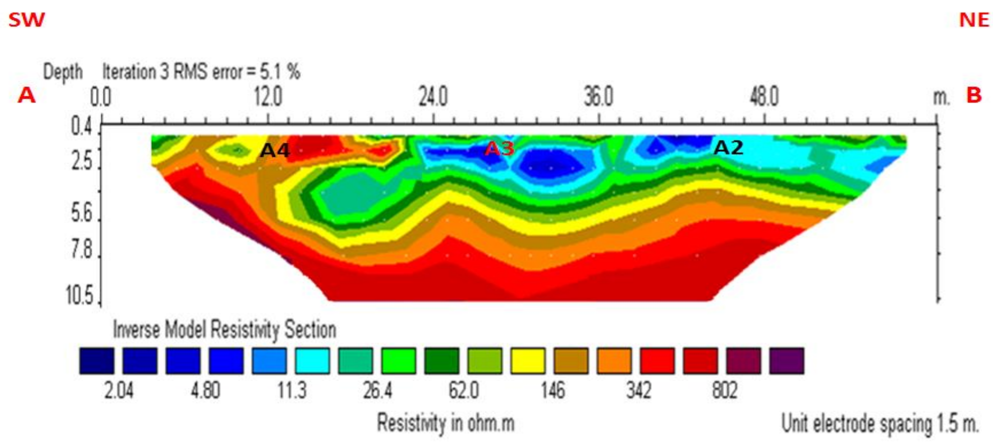

Fig. 5: Resistivity Tomography Pseudosection for Profile AB

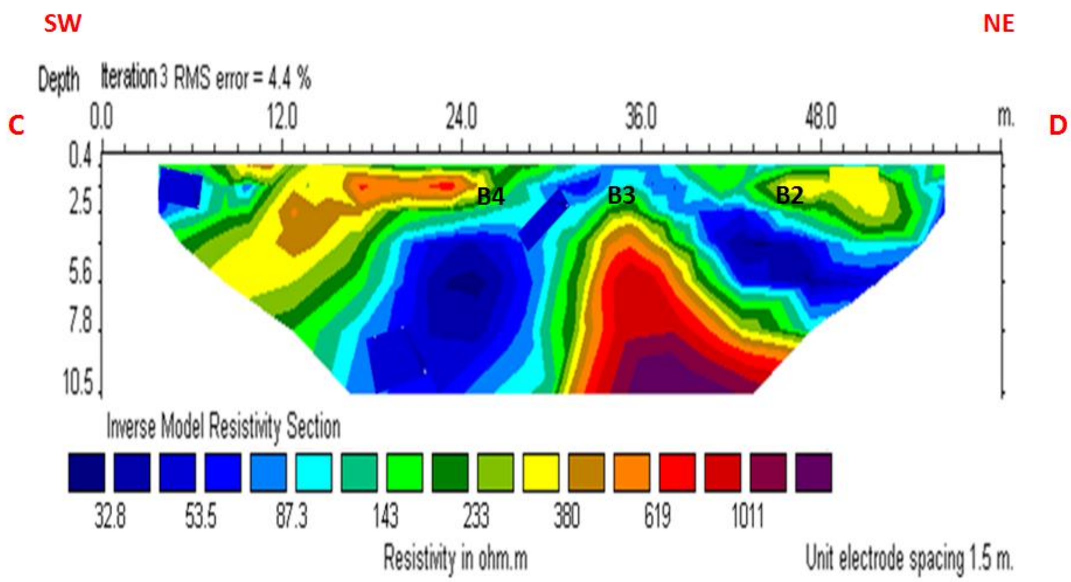

Fig. 6: Resistivity Tomography Pseudosection for Profile CD

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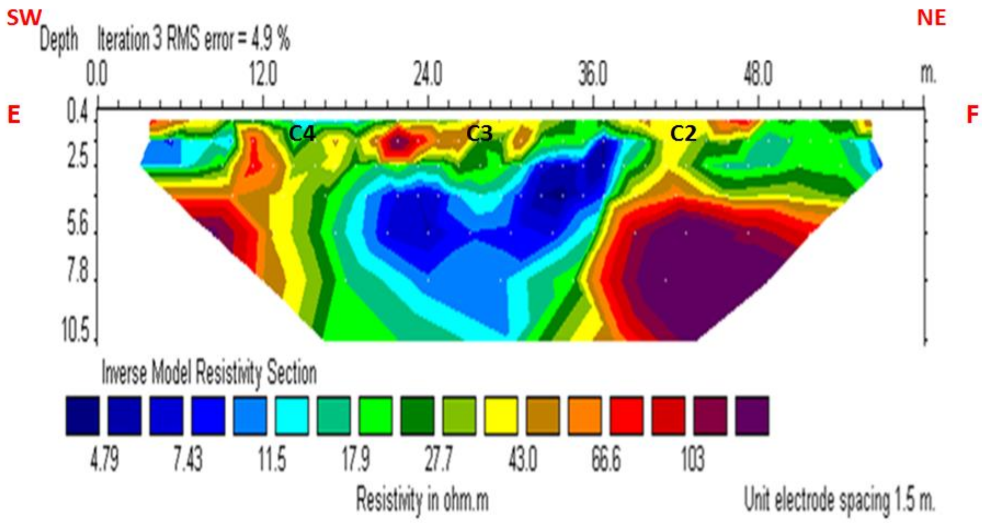

Fig. 7: Resistivity Tomography Pseudosection for Profile EF

Reconnaissance study showed that prior to building construction work the study area was dry during dry seasons and swampy during rainy seasons. The construction of the present structures in the area was followed by land reclamation which involved transfer of some earth material from different places and deposition in the study area. This most likely contributed to the lateral heterogeneity in the electrical resistivity of the subsurface at shallow depths in the study area.

Near – Surface Structures Underlying Profile AB

Profile AB is in the vicinity of a long building of class rooms located approximately at latitude 04° 47′ 27.68″ N and longitude 06° 19′ 14.58″ E. The building is affected by gaps between its walls and floors. The defect which appears like a trough has a maximum gap of about 5.0 cm at the centre and gently decreases to show little gap (≈ 2.0 cm) at the northeastern end and no gap at the Southwesthern end of the building.

The result of the 2-D electrical resistivity tomography data along profile AB (Figures 5) suggests that the subsurface at shallow (foundation) depth has less dense/loose or low resistivity soil layer at about the centre of the spread, flanked by dense/compacted or high resistivity soil layers. The delineated low resistivity soil layer at about the centre of the spread is overlain by the amplitude of the observed trough of the gap between the building's wall and floor.

Near – Surface Structures Underlying Profile CD

Profile CD is in the vicinity of a laboratory building located approximately at latitude 04° 47′ 26.15″ N and longitude 06°19′14.18″E. The building is affected by both diagonal and horizontal foundation based cracks. The result of the 2-D electrical resistivity tomography data along profile CD (Figures 6) suggests the existence of dense/compacted soil almost at the centre of the spread, flanked by loose (low density or uncompacted) soil. The compaction most likely is as a result of regular usage of the place than its surroundings by heavy duty vehicles, prior to construction work, and/or deposition of building materials, such as coarse soil which was covered by sandfill when the entire place was prepared for building construction work.

Near – Surface Structures Underlying Profile EF

Profile EF is in the vicinity of a long building of class rooms located approximately at latitude 04° 47′ 29.95″N and longitude 06° 19′ 16.74″. The building is affected by floor creaking which was sometimes accompained with popping sounds.

The resistivity range deduced from the 2-D electrical resistivity tomography data along the profile (Figures 7), when compared with the range, 1 – 100 Ωm, usually associated with clays, Telford *et al.* (1976) and Osemeikhian and Asokhia (1994) suggests that the subsurface at shallow (foundation) depth is predominantly clay. This further suggests that the anomalous zones are underlain by clay and clayey formations. The clay rich soil had resulted to creepy ground movement due to seasonal swells and shrinkages of the soil. This mechanism created the observed floor creaking.

Results of the Geotechnical Tests

The sources of the soil samples used for the tests and their numbers, A2, A3 and A4; B2, B3 and B4; C2,

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C3 and C4 are shown on Figures 5, 6 and 7 respectively. Figure 8 shows the result of one of the samples and Table 1 summarizes the results obtained in the geotechnical tests
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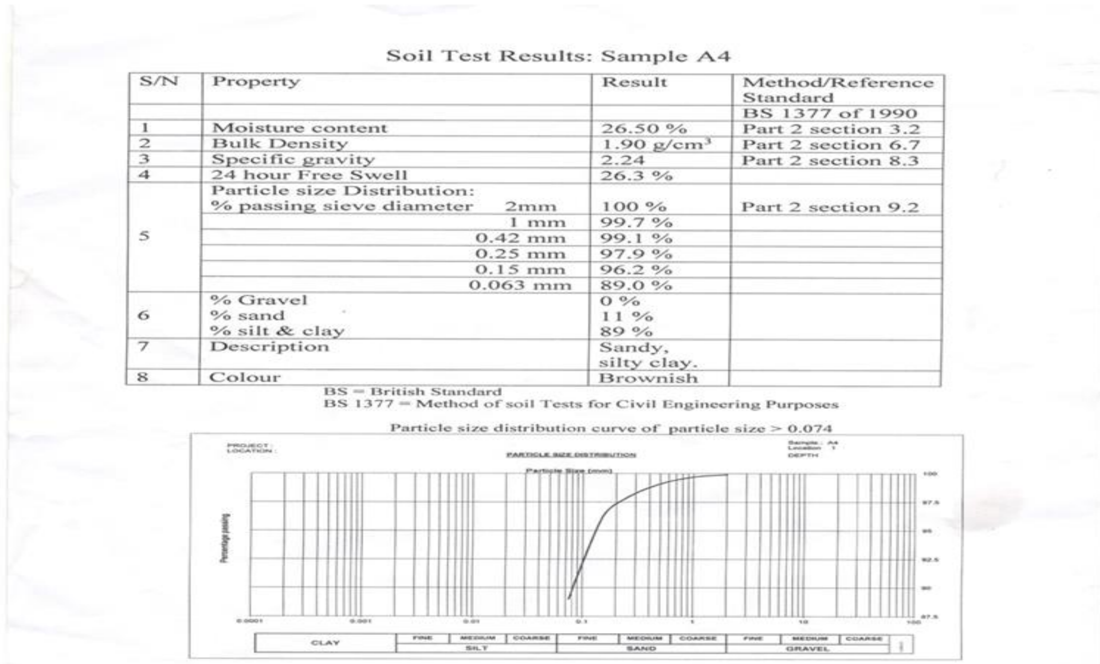

Soil Test Results: Sample A4

S/N	Property	Result	Method/Reference Standard
			BS 1377 of 1990
1	Moisture content	26.50 %	Part 2 section 3.2
2	Bulk Density	1.90 g/cm³	Part 2 section 6.7
3	Specific gravity	2.24	Part 2 section 8.3
4	24 hour Free Swell	26.3 %	
5	Particle size Distribution: % passing sieve diameter 2mm	100 %	Part 2 section 9.2
	1 mm	99.7 %	
	0.42 mm	99.1 %	
	0.25 mm	97.9 %	
	0.15 mm	96.2 %	
	0.063 mm	89.0 %	
6	% Gravel % sand % silt & clay	0 % 11 % 89 %	
7	Description	Sandy, silty clay.	
8	Colour	Brownish	

BS = British Standard
BS 1377 = Method of soil Tests for Civil Engineering Purposes

Particle size distribution curve of particle size > 0.074

Fig. 8: Results of Geotechnical Test of a Soil Sample in the Study Area

Table 1: Summary of the Results of the Geotechnical Test of the Soil Samples in the Study Area

Profile	Sample Source and Number	Predominant Soil Type	Depth of Source (m)	Approximate Resistivity Range (Ω)	Bulk Density (gcm^{-3})	Specific Gravity	Moisture Content (%)	Free Swell (%)
AB	A4	Sandy, Silty Clay	1.50	300 – 850	1.90	2.24	26.50	26.3
	A3	Clay	1.50	10 – 30	1.16	1.69	34.33	101.2
	A2	Sandy, Silty Clay	1.50	40 – 140	1.88	2.21	26.90	26.6
CD	B4	Sandy, Silty Clay	1.50	50 – 140	1.85	2.28	26.95	26.8
	B3	Coarse Sand, fine aggregates, probably sandfill	1.50	400 – 1000	2.08	2.71	04.40	0.0
	B2	Sandy, Silty Clay	1.50	50 – 140	1.88	2.23	26.97	26.7
EF	C4	Clay	0.50	10 – 100	1.14	1.77	36.15	98.7
	C3	Clay	0.50	10 – 100	1.11	1.74	36.25	106.3
	C2	Clay	0.50	10 – 100	1.13	1.76	35.80	103.7

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The results of the geotechnical test suggests that the layer of the soil directly underlying the building at A3 (Figure 5) has less bulk density and specific gravity than A2 and A4. This suggests that a loose soil layer is flanked by compacted soil layers. Owing to difference in texture and high moisture content of A3 relative to A2 and A4, it is a weak zone which resulted to the subsidence of the floor overlying it.
Based on the interpretations given in the foregoing, a model was put forward for the structural failure of the building on profile AB. The model is presented in Figure 9. The figure suggests that a less dense soil layer (clay), underlying the 'trough' is flanked by compacted soil layer. Owing to high moisture content (34.33 %) and swell (101.2 %) of the clay relative to the adjacent soil layers the water seeping into the former caused it to swell during wet season resulting to enormous forces which lifted the tiled floor up. The clay lost its water during dry season and its shrinkage caused the subsidence of the floor resulting to the observed gap between the floor and the wall.

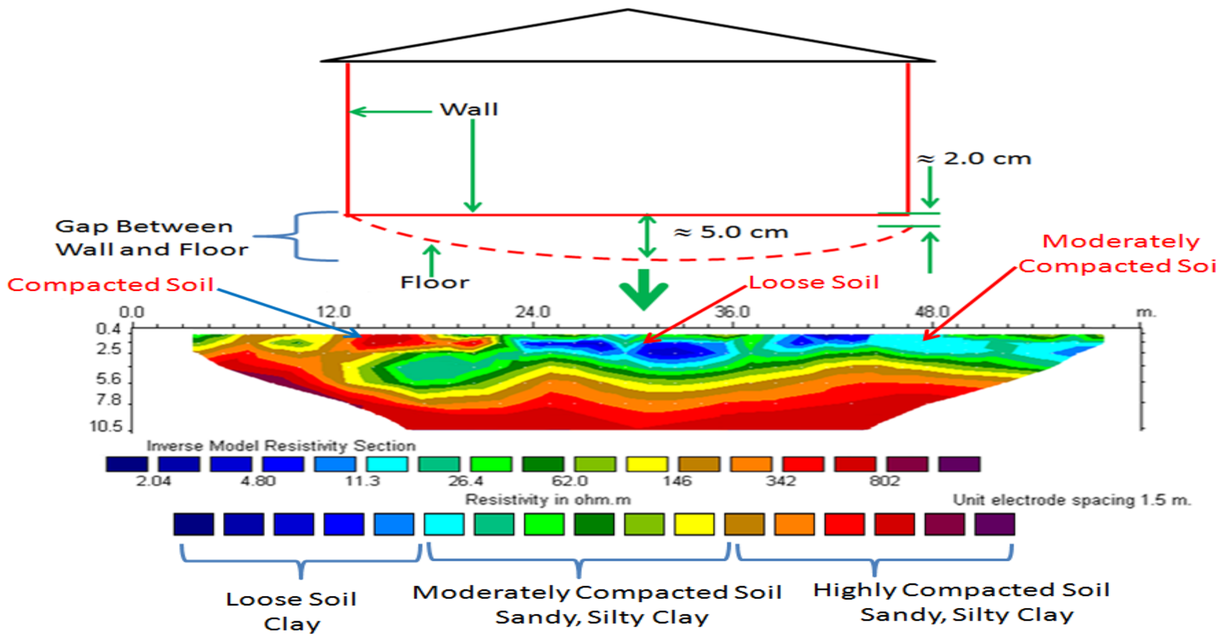

Fig. 9: Model Representation of the Mechanism of the Structural Failure that Affected the Building on Profile AB

The results of the geotechnical tests of the soil samples collected from B2, B3 and B4 along profile CD (Figure 6) suggest that the layer of the soil directly underlying the building at B3 has higher bulk density and specific gravity than B2 and B4. This suggests that a compacted soil layer is flanked by loose soil layers. These differences in soil compaction laterally most likely led to differential settlement of the building. The diagonal crack most likely was caused by the resistance the underlying soil layer (Coarse Sand) offered to the building's settlement relative to the Sandy Silty Clay which offered less resistance. The Coarse Sand with fine aggregates most probably was artificially deposited there as building material. The difference in compaction laterally of the soil layers in the area is most likely due to the presence of different soil types, uneven sand filling and heavy truck/vehicular movements in some parts than others.
A model was suggested for the structural failure of the building on profile CD (Figure 10).

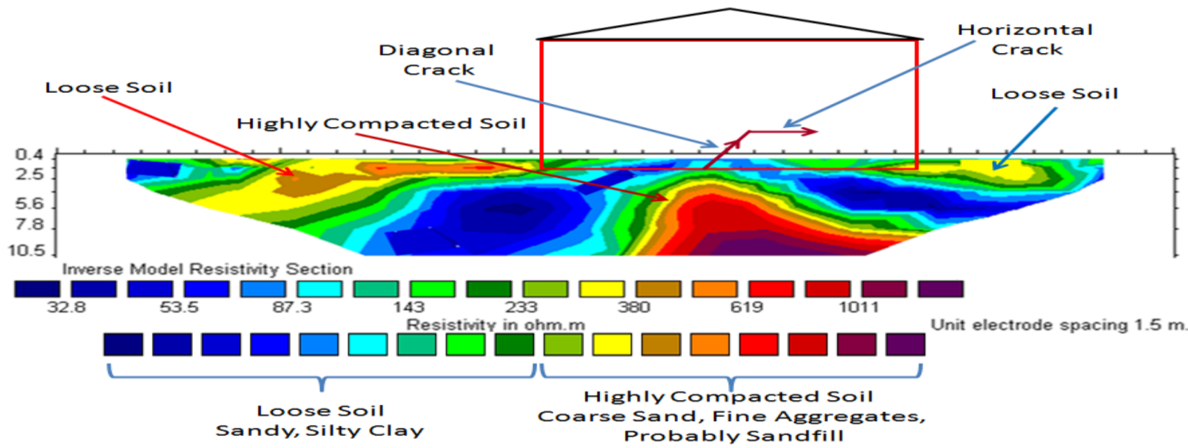

Fig. 10: Model Representation of the Mechanism of the Structural Failure that Affected the Building on Profile CD

The diagonal crack directly overlies B3 while the horizontal part overlies B2. This suggests that the cracks originated from uneven or differential settlement of the building. B3 offered more resistance to the downward movement (settlement) of the building than B2. That is, the crack most likely originated at the foundation of the building overlying B3 as 'diagonal crack' due to differential resistance to its settlement at B3, B3 and B4 and this crack was transmitted to other parts of the building overlying B2 as 'horizontal crack'.

The geotechnical parameters obtained from the soil samples collected from C2, C3 and C4 along Profile EF (Figure 7) suggest low values of bulk densities and specific gravity of the soil layers directly underlying the building's floor. Results of the tests showed that the range of the volumetric increase of the soil samples is 98.75 – 106.3 % (Table 1) for the clay soil directly underlying the building. According to Gibbs and Holtz (1956), soils with free swell values of 100% or more are associated with clays which could swell considerably when wetted. Clay particles are called layer silicates as the lattice structures form layers so that many clay particles resemble minute fish scales (Graymount, 2006). As a result some clays have an enormous surface area per gram. The large surface area of the clays combined with the electrostatic attraction between water and clay can result in enormous forces in the process of swelling and shrinkage of clays (up to 10,000 atmospheres of pressure), such that the swelling of clay, can lift structures off their foundations (Graymount, 2006) and its shrinkage can cause partial subsidence of the structure.

Recommendation and Conclusion

The results of this study have suggested that differential or uneven settlement arising from soils of different types and compaction directly underlying different parts of the same building most likely caused the cracks on the building's walls. Also this most likely caused the existing gaps between the building's wall and floor. It is therefore recommended that in subsequent construction of buildings in the university and its environs with similar geology, measures should be taken to minimise structual failure. Building Engineers in the area should ensure that each building is directly underlain laterally by the same type of soil having no significant difference in compaction. Geophysical surveys and geotechnical studies in any proposed building site are necessary to delineate the types of soils and compaction directly underlying each proposed building project. It is necessary to undertake soil treatment as proposed by Alayaki *et al*., (2017) if the soil is rich in clay and significantly have lateral variation in compaction.

The structueral failure of some buildings in the premises of Federal University Otuoke, Nigeria, was investigated using electrical imaging technique and geotechnical tests involving moisture content, bulk density, specific gravity, free swell and texture determinations. The results of the 2-D electrical resistivity imaging and geotechnical tests showed that the subsoil at shallow depths underlying the buildings are predominantly Sandy Silty Clay, clay and Coarse Sand, fine aggregates, probably sandfill. The wide ranges of the moisture content, bulk density, specific gravity and free swell of the soil layers directly underlying the buildings suggest that the structural failures are most likely initiated by differential settlement caused by significant variation laterally in the compaction of the soils and clay swelling.

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