Geophysical Assessment of Foundation Depths around a Leaning Superstructure in Zaria Area, Northwestern Nigeria using Electrical Resistivity Tomography.

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ABSTRACT

This study was carried out to assess the foundation depths around a building site in Zaria area, north-western Nigeria using electrical imaging technique. The affected structure is a three storey building leaning at relative rotational angle of about 5.5^0 and having severe foundation-based cracks. The site lies within the Basement Complex of northern Nigeria. Model *SAS 4000* Terrameter aided by Electrode Selector was used for data collection while *version 3.4 RES2DIV* software was used for data processing. Eight profiles of various spread lengths and offsets from the building were laid parallel to Building's walls. Inversion model resistivities of range 1-1000 Ωm were obtained and this range encompasses the resistivities for sand, clay, sandy clay, soil water and laterite. These results were complemented and confirmed by seismic refraction tomography and free swell test of soil samples at foundation depths. The interpreted results show that active clayey soil ratio of 0.7 – 2.5 swell increase, shallow aqueous zones and contrasts in consolidation of materials at foundation depths most likely led to creepy ground movements which affected the stability of the building. The results also show that anticline and synclinal structures underlie the superstructure and these indicate the occurrence of undulated subsurface at the vicinity of the building. These thereafter most probably gave rise to differential consolidation settlements which has led to both the structural cracks and progressive E-W leaning of the superstructure at about 0.09^o per annum.

(Keywords: superstructure, foundation, geology, anticline, synclinal structures, soil stability)

INTRODUCTION

In building construction, poor soil stability is one of the factors that cause havoc. This is because some soils are very sensitive to moisture gain or loss. Certain clay soils for instance, can expand multiple times in volume if they get saturated and when there is loss of water in them, they shrink in volume. This expansion and shrinkages of clayey soils cause foundation cracks on buildings shortly after they are built in the process of their settlement. The understanding of swelling and shrinkage characteristics of soils is very important in solving engineering problems commonly associated with the construction of buildings, dam and highways. Subsidence and heave caused by moisture content variation especially in clay soils is a major problem throughout the world, and may be made worse as global warming increases local climate variability.

Foundation cracks on buildings occur as a result of differential movement on the building. The size, shape, pattern and location of foundation cracks on a building, when correlated with other site and construction conditions, help to distinguish among probable causes of foundation based failures (Tim, 2002). Building foundation may be active due to horizontal wall movement, wall tipping, leaning due to wall bulging or movements at a constant rate which may be accelerating or decelerating seasonally. When this happens, professional inspection is required. Settlement could be as a result of weakness of the soil beneath the foundation or beneath the building's column supports. In the process of the settlement, the soil shrinks due to moisture loss, and gets compacted properly. Some settlements are due to unstable soil and structures above concealed cavities or organic material, while others are due to expansive soils. At some

places, it is due to the lifting by growth of ice, the crystallization of gypsum, or hydration of anhydrite in rocks on which they are founded. Sometimes it occurs because the foundations are located on landslides thereby moving laterally and vertically, which is usually at different speeds. Settlements could also be due to shock, vibration or regional subsidence (Sands, 2002; Zeynal, 2003; Tomlingson and Boorman, 1999).

According to Burland *et al.* (1977), visual appearance, serviceability (or function) and stability must be satisfactory when considering the limiting movement of a structures. Excessive tilting may occur and this could lead to the complete collapse of a structure. The degree of damage caused by settlement is to some extent dependent on the sequence and time of construction operations (Tomlingson and Boorman, 1999). In Zaria area, many buildings are affected by foundation based structural defects. They are affected by varieties and degrees of instability ranging from severe wall cracks to leaning. These structural defects have sometimes led to the collapse of the affected parts of the buildings. This state of structural failure has given geosciences' community in Zaria area deep concern. This study is aimed at delineating the geologic features and failure mechanisms which are causative to the leaning of the superstructure in Zaria area, Nigeria using electrical imaging technique.

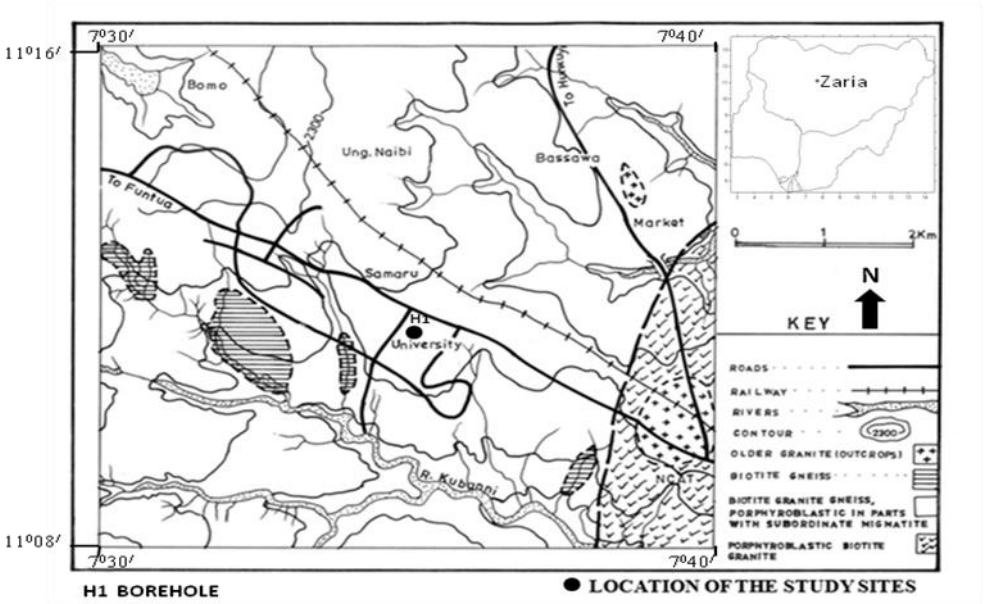

Figure 1: The Geology Map of the Study Area Showing the Location of the Study Site.

The study site is a students' hostel building in Ahmadu Bello University Samaru, Zaria, Nigeria which consists of 48 rooms. It is a three storey building completely constructed in 1975 using masonry blocks (Figure 2a). The topography of the building's site is relatively flat with a minor gentle slope trending in north-south direction. Vertical, diagonal and horizontal cracks are shown on most parts of the building walls. Some of the cracks are rooted from the building's foundation; however, some diagonal cracks which are rooted at the corners of the building have put the superstructure at high risk. There is no evidence of sinkholes, random depression, irregularity in the ground surface, or wrinkling noticed at the site. There is also no indication of significant soil creep as may be evidenced by leaning trees yet; there is loss of *visual appearance*, *function* and *stability* which are originally intended for the building (Figure 2).

It was also observed that the neighboring buildings of similar size, built of similar material and at the same time around the one under study, have not shown similar kind of distress. These suggest that the failure of the building is most probably entrenched on the subsurface. This therefore calls for geophysical investigation.

During the reconnaissance survey, the building's maximum settlement depth and angle of leaning were measured to be 0.675 m and 5.50^0, respectively. The university booked the structure for demolition 12 months after the survey because it could not reach a viable solution that can bring the building to a constant state of dynamic equilibrium. Figures 2b, 2c and 2d show the danger due to some of the cracks on the building and the leaning angle.

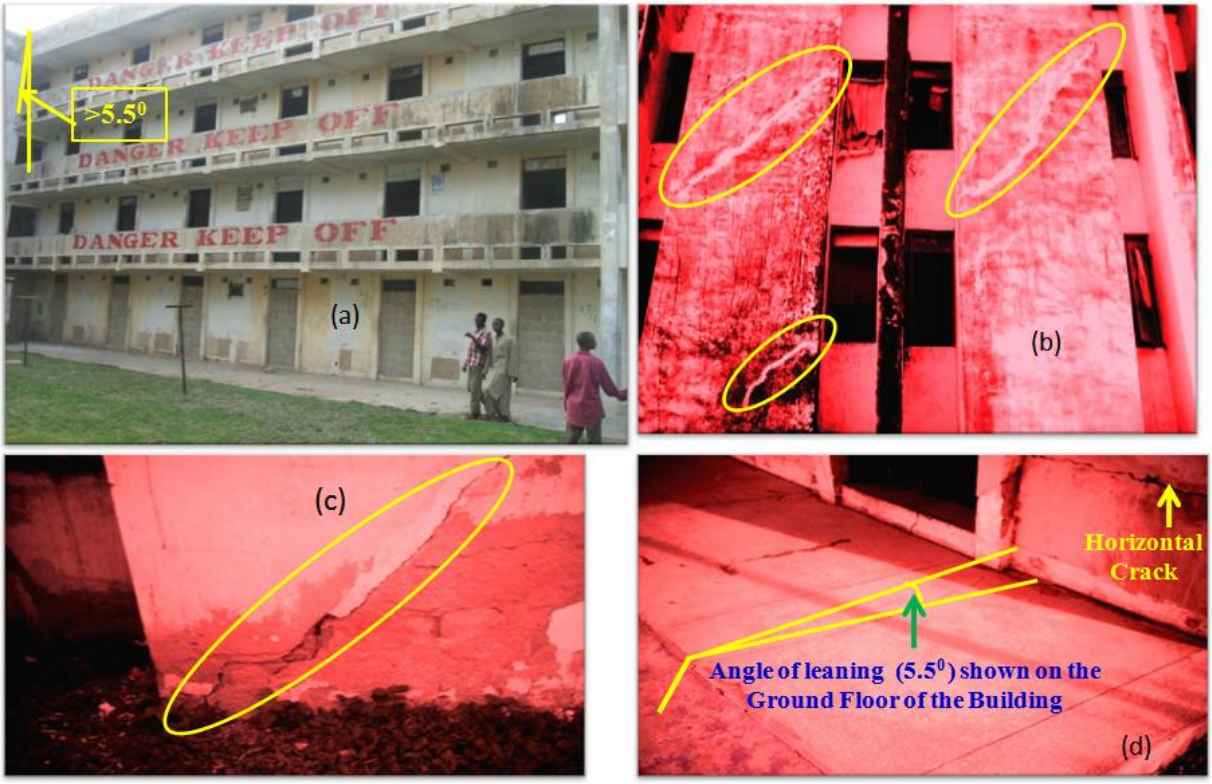

Figure 2: Danger of Some Severe Horizontal and Diagonal Cracks at Some Parts of the Building. **(a)** Shows Isometric View of a Part of the Building under study (Leaning), **(b)** and **(c)** Show Diagonal Cracks at the Rear Side of the Building, and **(d)** Shows Angle of Leaning at Floor and a Horizontal Crack at the Front Side of the Building.

THE GEOLOGICAL SETTING OF ZARIA AREA

Zaria area is located between latitude $11^o03'$N and $11^o11'$N and between longitude $07^o12'$E and $07^o47'$E on an elevation of about 670 m above the mean sea level. It falls within the basement complex of Northern Nigeria. It is underlain by precambrian rocks occurring in a dissected portion of the crystalline Zaria–Kano extensive peneplains. Residual granite inselbergs, the largest of which is the Kufena Hill, provide the main relief in the area (Wright and McCurry, 1970). Four groups of rocks define the basement complex of northern Nigeria namely, Older Metasediment, Younger Metasediment, the Older Granite and the Younger Granite (McCurry, 1970). The study site is part of Zaria batholiths which comprises series of granites that intruded the country rock gneisses (Ike 1988). Figure 1 shows the geological map of the Zaria area where the study site is located.

The climatic and the hydrogeologic conditions control the surface and the subsurface water in the area. Chilton and Smith-Carington (1984) and Jones (1985) suggested that the weathered rocks form the important aquifer in the crystalline rocks, while Clark (1985) and Edet *et al,* (1994) held the view that ground water occurs in fractures of the bedrock. However, Offodile (1983), Grey *et al* (1985), Adanu (1988), Wright (1992) and Alagbe (2002) have indicated that ground water occurs in a continuum within both the weathered basement and fractures within the

basement rocks. Economically, Zaria is very rich in ceramic materials and water. Clay is a major constituent of its Younger Alluvium (Wright and McCurry, 1970).

METHODOLOGY

Electrical resistivity imaging was carried out along eight (8) profiles laid around the building under study in order to delineate the resistivity of the subsurface materials. The technique was used so as to delineate the overburden, weathered zones, fractured columns and where possible, the bedrock at the site. Apparent resistivity data were collected with a Lund Imaging system comprising *Terrameter SAS 4000* and Electrode Selector *ES464* which is a relay switching unit having 42 electrode takeouts. Six (6) out of the eight (8) profiles for the resistivity survey were laid in N-S direction while the other two (2) were laid in W-E direction (Figure 3). Electrode spacing ranged from 1.50 m to 5.00 m depending on the length of each profile which depended on available space. It was ensured that the ground was amenable to the electrode insertion. The centre of each spread was located midway in the vicinity of the building to ensure that the deepest of the probes is in the vicinity of the building under study. A few electrodes were unavoidably skipped during the data collection owing to the presence of special features like concrete slabs and road tars. Table 1 shows the summary of the data collection at the site.

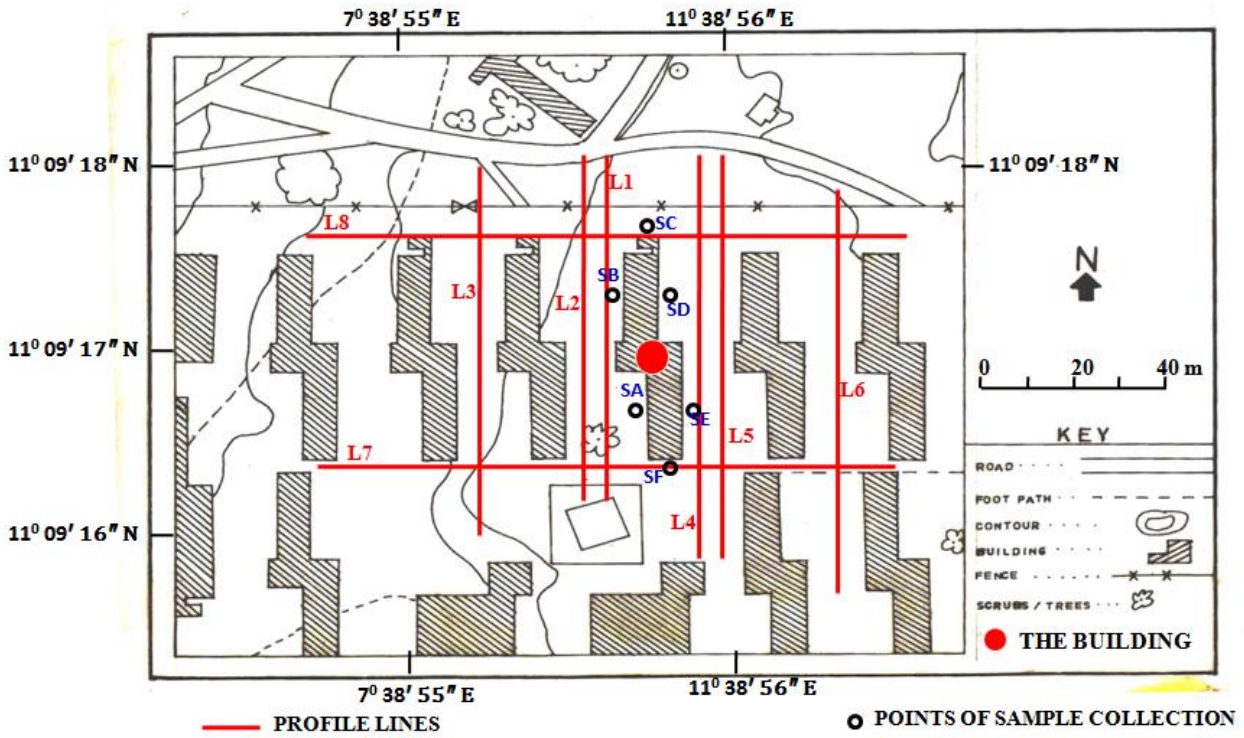

Figure 3: The Study Site Showing the Profile Lines Occupied for the Investigation and the Points of Sample Collection.

Table 1: Summary of the Parameters Used for Data Collection at the Study Site.

Profile Name	Profile Orientation	Offset of profile from the building under study (m)	Profile Length (m)	Electrode Spacing (m)	Number of skipped electrodes	Remark
L1	N-S	2.5 west of the building	80.0	2.00	1	-
L2	N-S	7.5 west of the building	60.0	1.50	-	-
L3	N-S	5.0 west of the building next to the building	60.0	1.50	_	Profile across a buried tank
L4	N-S	2.5 east of the building	60.0	1.50	-	_
L5	N-S	7.5 east of the building	60.0	1.50	-	_
L6	N-S	5.0 east of the building next to the building	80.0	2.00	3	_
L7	E-W	3.5 south of the building	100.0	2.50	4	_
L8	E-W	3.5 north of the building	100.0	2.50	-	Profile across several sewage pipes

INTERPRETATION

RES2DINV Ver.3.4 issued by "Geotomo Software" was used for the processing of the raw data. The software automatically determines a two-dimensional (2-D) resistivity model of the subsurface (Griffiths and Barker, 1993). A forward modeling subroutine was used to calculate the apparent resistivity values, and a non-linear least-squares optimization technique (deGroot-Hedlin and Constable 1990, Loke and Barker 1996), was used for the inversion routine based on the smoothness-constrained least-squares method (Sasaki, 1992).

The least–squares inversion was used to convert the measured apparent resistivity values to true resistivity values and plots were obtained in cross – sections. Hence, three sections namely the observed section, calculated apparent resistivity pseudosections and the inverted model section were obtained. In situation where much discrepancy existed, the iteration was repeated until the minimum discrepancy was reached. Due to sharp resistivity contrast noticed in some sections, robust constrain inversion modeling technique was also used for the inversion of some of the profiles.

Figures 4-11 show some of the 2D model electrical resistivity sections obtained for the eight profiles. The range of the root mean square (RMS) errors shown on the pseudosections 3.4% -5.1% which is $\leq$ 5%, indicates that there were good fits between the measured and the calculated apparent resistivity data.

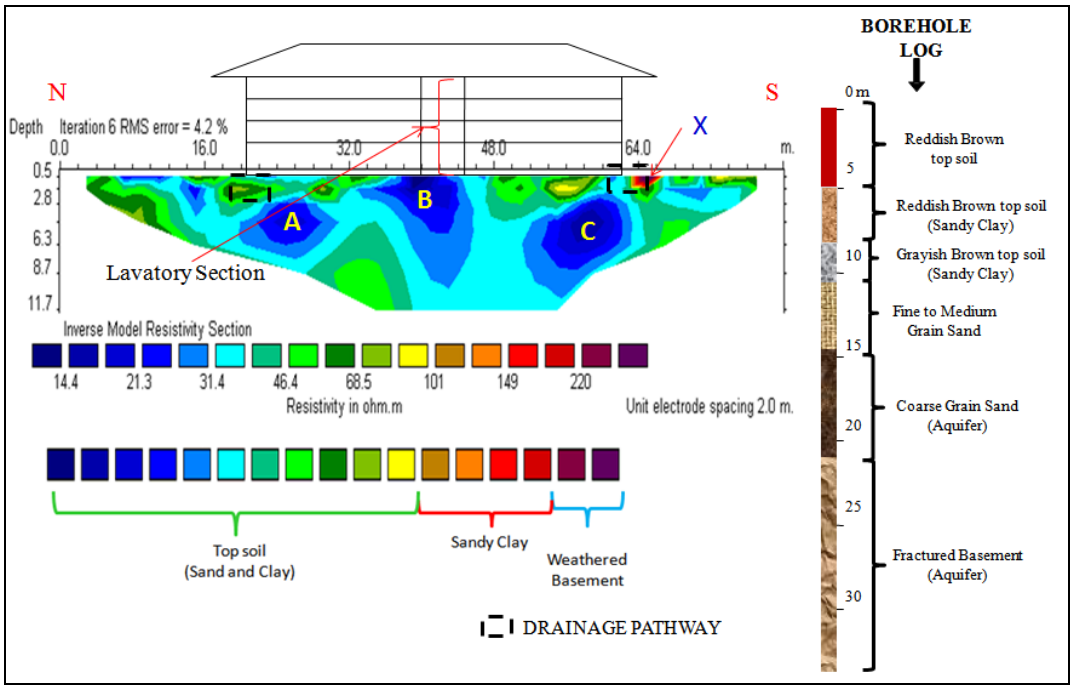

Figure 4: 2D Inversion Model Resistivity Section for Profile L1.

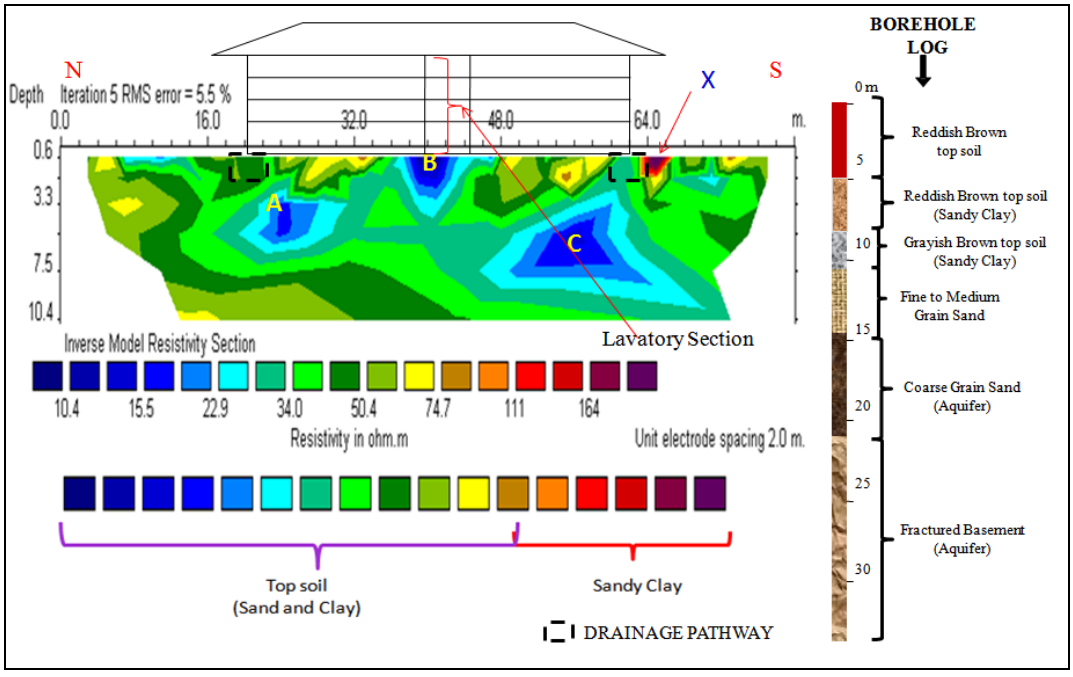

Figure 5: 2D Inversion Model Resistivity Section for Profile L2.

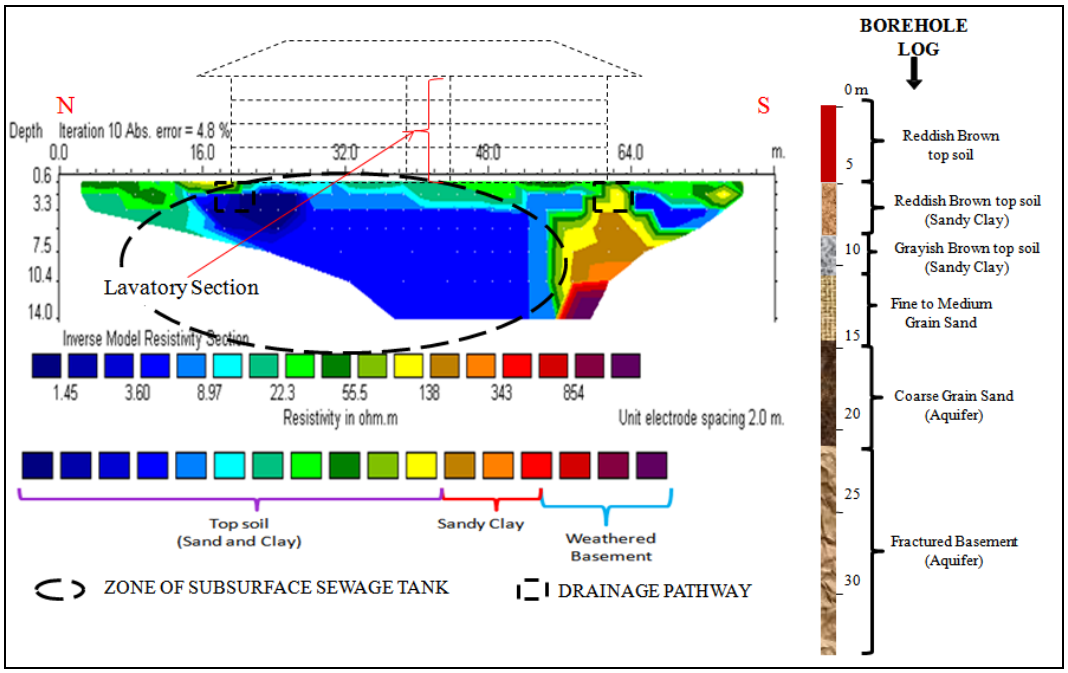

Figure 6: 2D Inversion Model Resistivity Section for Profile L3.

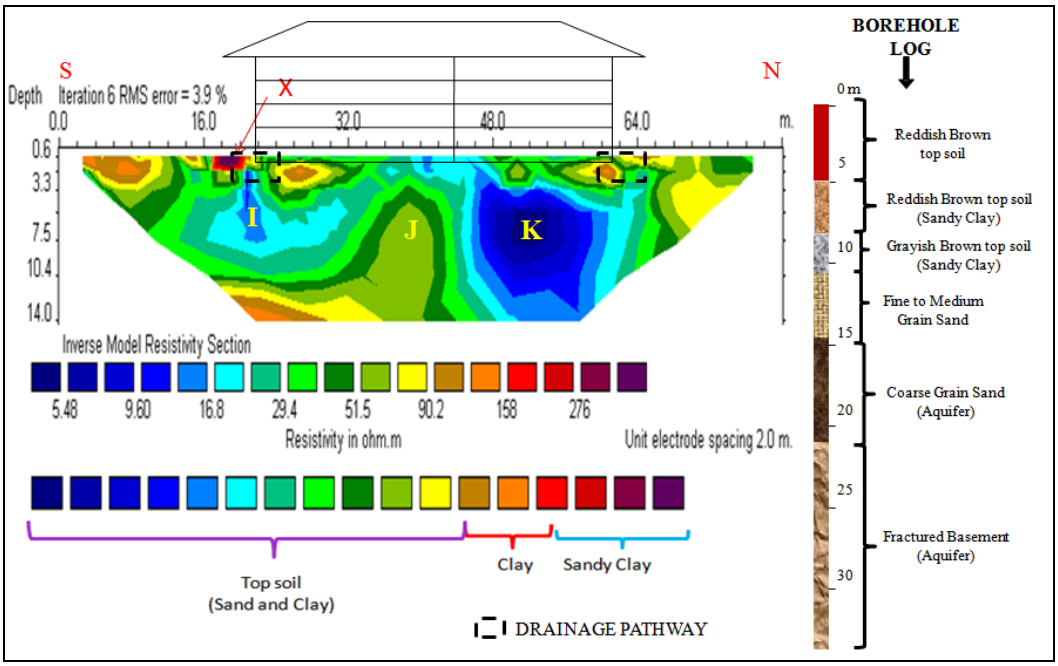

Figure 7: 2D Inversion Model Resistivity Section for Profile L4.

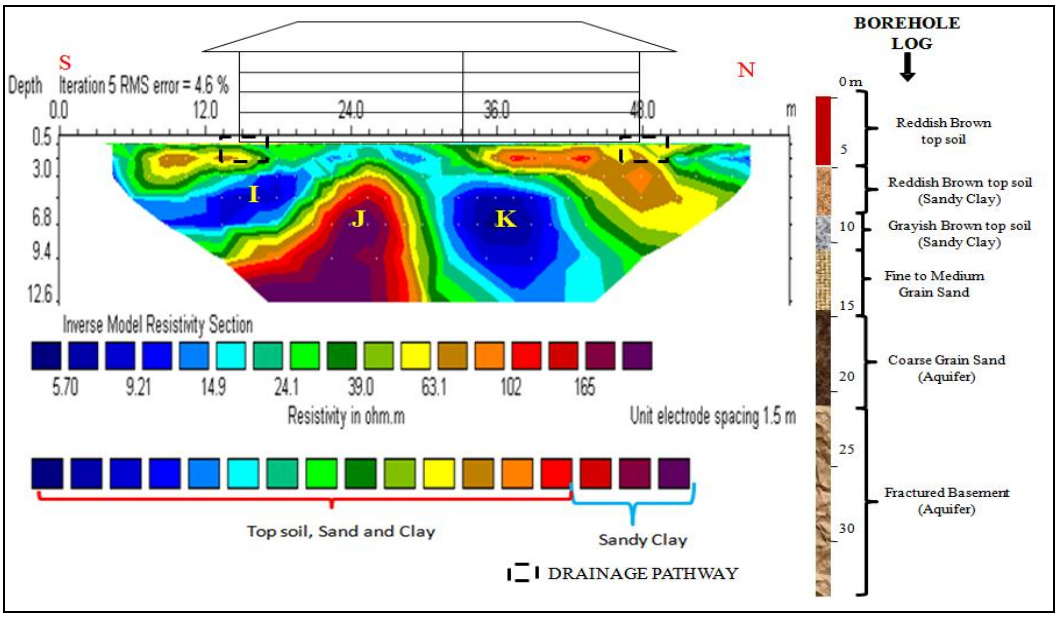

Figure 8: 2D Inversion Model Resistivity Section for Profile L5.

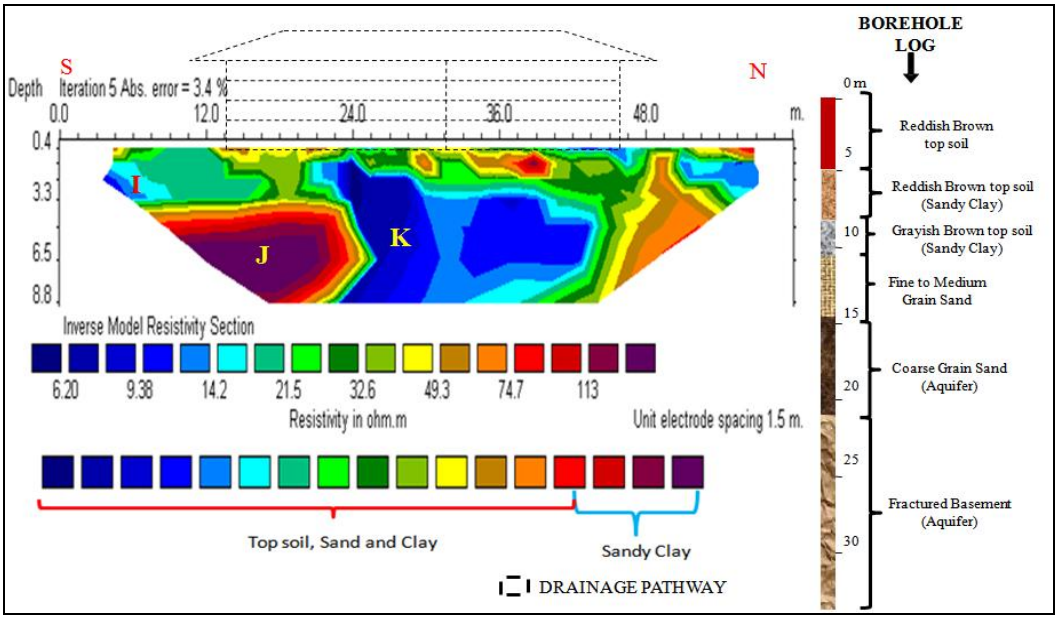

Figure 9: 2D Inversion Model Resistivity Section for Profile L6.

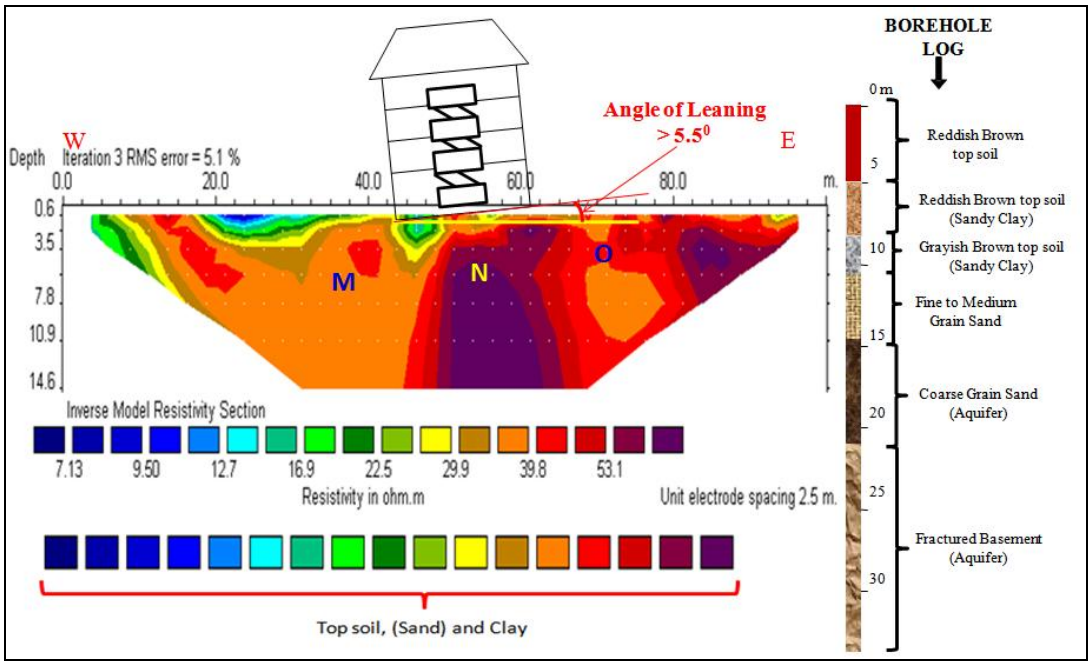

Figure 10: 2D Inversion Model Resistivity Section for Profile L7.

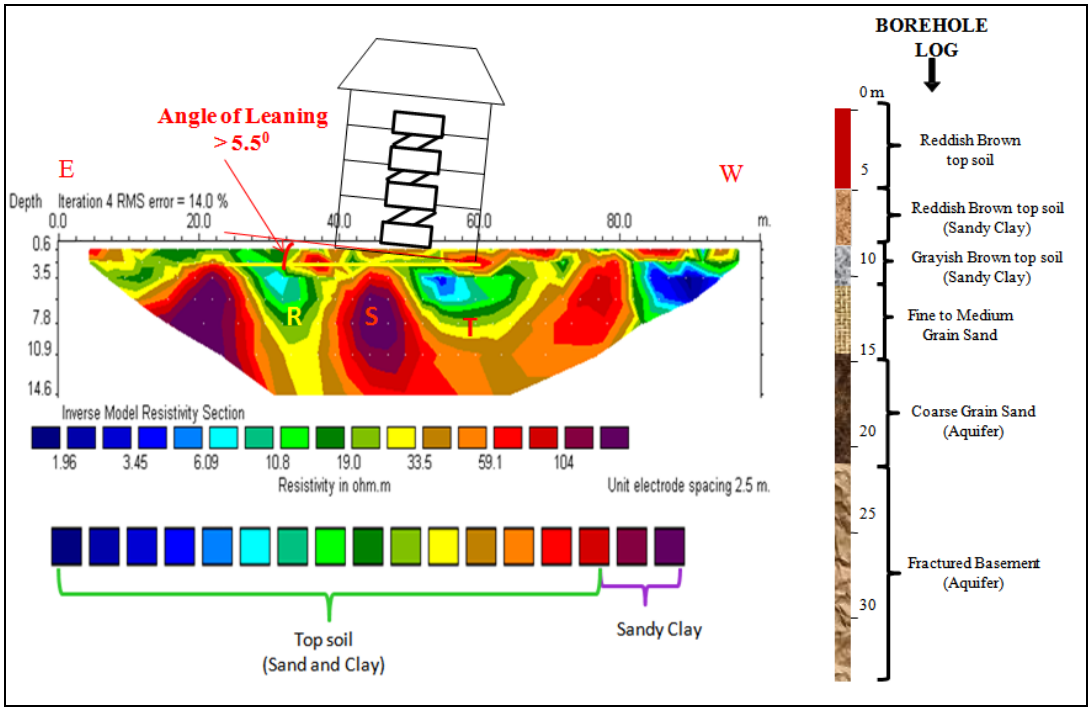

Figure 11: 2D Inversion Model Resistivity Section for Profile L8.

The geoelectric sections obtained are characterized by resistivity range of 1–1000 Ωm .

This range indicates the occurrence of sand, sandy clay, clay and soil water whose ranges are; 10 - 1000 Ωm , 100 – 200 Ωm , 1-100 Ωm and 10 -100 Ωm , respectively (Table 2).

First of all, borehole log recorded from the closest borehole to the building H1 (Figure 3) was obtained. The borehole logs which were interpreted by Hydro Skill and Engineering Services, Kaduna (2005) were used as a control for the interpretation of the entire pseudosections obtained in this survey.

Table 2: Summary of the Representative Resistivities for the Interpreted Materials.

Interpreted Subsurface Material	Standard Resistivity (Ωm)
Sand	500-1000
Sandy Clay	100-200
Clay	1-100
Gneiss	6.8×10^4(wet) – 3×10^6(dry)
Granite	3×10^2-10^6

DISCUSSION

The 2D model tomograms of all the profiles are characterized by relatively low resistivity values of the range (1-1000 Ωm). This suggests that the subsurface at the site is less compacted and relatively conductive. The pseudosections reveal other features which have physical properties that can lead to structural failure.

Profiles L1 and L2 (Figures 4 and 5) show three distinct zones of relatively low resistivities namely; A, B and C. These zones in the range of (10-30 Ωm) suggest that they are most probably saturated clayey zones. In profile L1 (Figure 4), zones A and C directly underlie a major drainage path which is characterized by severe cracks and breakages, while zone 'B', directly underlay the lavatory section of the building which is also characterized by severe foundation-based cracks. The cracks and breakages which occur on both the drainage path and the lavatory section of the building provide route for seepage of sanitary effluents into the ground. This most likely contributed to the distinct saturation at A, B, C in the foundation depths. These three zones (A, B and C) are also shown on profile L2 (Figure 5) pseudosections as in profile L1 but with reduction in size and at greater depths. It can therefore be deduced that beyond the usual occurrence of swelling in wet seasons, the frequent seepage of the sanitary effluents due to continuous domestic activities most likely sustains high level of saturation in the subsoil throughout the year. This invariably might have led to the subsurface weakness at the western side of the building.

The three zones are not shown in profile L3 (Figure 6) which is located at an offset of 5.0 m from the building next to the one under study westwards. Figures 7-9 show three other significant zones namely I, J and K, which are relatively low, high and low resistivity zones respectively. The relatively high resistivity zone J, suggests the presence of a more consolidated material which underlie the building. Since J is central in the section, it most probably provides strong support at the eastern side of the building under study. The continuation of the zones I, J and K are also shown on profile L5 (Figure 8) at almost the similar positions with slight reduction in the resistivity range. Profile L6 (Figure 9) shows J and K which are more to the left of the pseudosection while the zone 'I' was not significantly delineated. This implies that the three features I, J and K trend southwards with increase in the offset from the building under study.

There is a noticeable but insignificant portion on the pseudosection region of a relatively high resistivity (X) at the top right of the profiles L1 and L2 (Figures 4 and 5), and at the top left of Profiles L4 (Figure 7). This zone by its relative resistivity value (> 1000 Ωm) reveals that it is most likely concrete foundation pavement which underlay the major passage linking hostel buildings. Profiles L7 and L8 (Figures 10 and 11) show the end views of southern and northern subsurface of the building. Profile L7 shows a relatively high resistive zone N which directly underlay the building. It is notable that the zone N is anticline in shape and it is flanked by relatively low resistive zones M and O. The relatively high resistive zone N most likely pivoted the leaning of the building in the E-W direction towards the less resistive zone M (Figure 10). Profile L8 (Figure 11) shows undulating subsurface characterized

by relatively low, high and low zones R, S and T respectively. The pseudosection (Profile L8) therefore reveals that the building is underlain by a relatively high resistive zone (S) which most likely pivots the tilting of the building towards the less resistive flank (T).

Seismic refraction tomography was also carried out along profiles L7 and L8 (Figures 12 and 13) for the confirmation of the results. The seismic sections reveal that the subsurface at the southern side of the building gently slopes in E-W direction (Figure 12) which confirms the E-W leaning towards the side M in the resistivity pseudosection of profile 7 (Figure 10).

Similarly, the northern side of the building as shown in the seismic section is directly underlain by a synclinal structure (Figure 13) towards which the building leans. This also confirms the undulating subsurface in the resistivity pseudosection of profile 8 (Figure 11) in which the building leans in W-E direction. Both the dipping and the synclinal structures shown on the seismic pseudosections suggest that they most likely contribute to the structural failure of the building.

Free swell test was carried out on eighteen (18) subsoil samples which are cored from 6 spots around the building (Figure 3) at foundation depths of 1.0 m, 1.5 m and 2.0 m, respectively. Results of the test show that the range of the volumetric increase of the saturated clayey soils lies within the ratio of 0.7-2.5 (Table 3).

According to Gibbs and Holtz (1956), soils with free swell values less than 50% are not likely to show expansive properties but values of 100% or more are associated with clays which could swell considerably when wetted. The test results also show that the subsoil is relatively more expansive at the western side of the building toward which the building leans than at the eastern side of it.

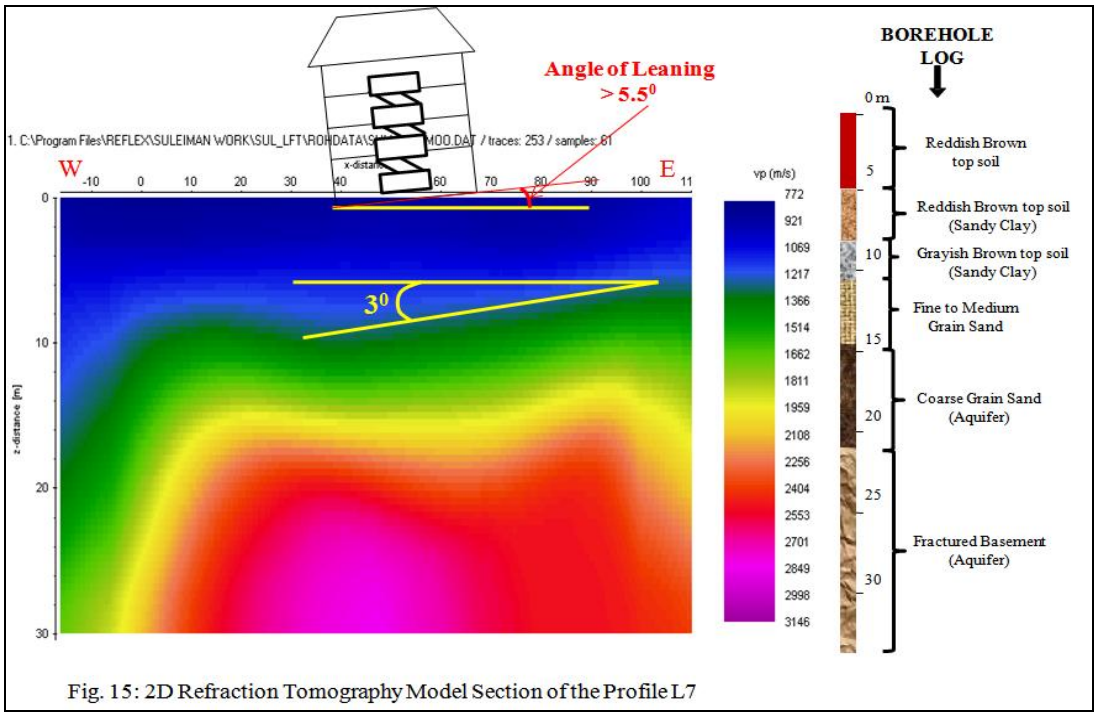

Fig. 15: 2D Refraction Tomography Model Section of the Profile L7

Figure12: 2D Refraction Tomography Model Section for Profile L7.

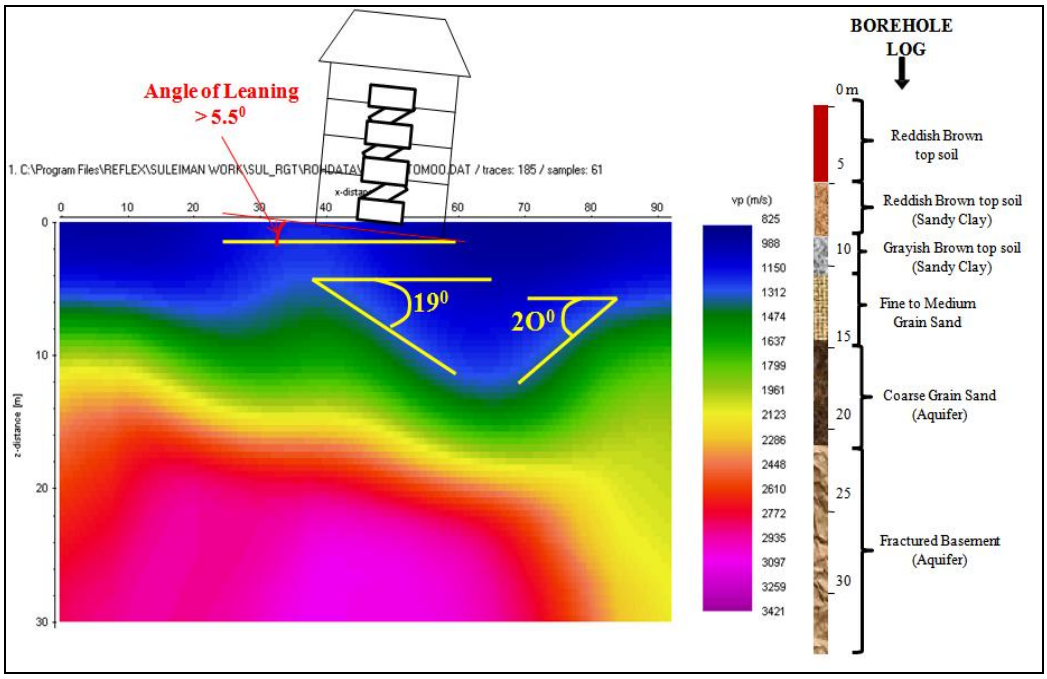

Figure 13: 2D Refraction Tomography Model Section for Profile L8.

Table 3: Results of the Free Swell Test on the Soil Samples Collected from Foundation Depths Around the Superstructure.

Building Side	Sample Number	Depth (m)	Initial Vol. (ml)	Final Vol. (ml)	Free Swell Increase
Western	SA1	1.00	10.0	26.50	1.65
,,	SA2	1.50	10.0	27.50	1.75
,,	SA3	2.00	10.0	24.00	1.40
,,	SB1	1.00	10.0	22.00	1.20
,,	SB2	1.50	10.0	29.50	1.95
,,	SB3	2.00	10.0	35.00	2.50
Northern	SC1	1.00	10.0	28.50	1.85
,,	SC2	1.50	10.0	25.00	1.50
,,	SC3	2.00	10.0	27.50	1.75
Eastern	SD1	1.00	10.0	26.00	1.60
,,	SD2	1.50	10.0	22.50	1.25
,,	SD3	2.00	10.0	22.00	1.20
,,	SE1	1.00	10.0	24.50	1.45
,,	SE2	1.50	10.0	23. 00	1.30
,,	SE3	2.00	10.0	23.50	1.35
Southern	SF1	1.00	10.0	17.50	0.75
,,	SF2	1.50	10.0	17.00	0.70
,,	SF3	2.00	10.0	25.00	1.50

On analysis, the weight of the superstructure was initially supported by a seemingly stable subsurface at the end of its construction in 1975 during which the immediate settlement might have taken place. After the immediate settlement, the building might have commenced its consolidation settlement which is now observed to be differential. The building probably underwent deceleration at the eastern side of it than at the western side of it during its consolidation settlement. Since the foundation depths (1-2 m) of this site by interpretation, is characterized by clayey soils, it implies that creepy ground movement due to seasonal swells and shrinkages of the soils at foundation depths might have contributed to both the distress on the building and its differential settlement.

The angle of leaning of the building was monitored from the time of the reconnaissance survey till date and the estimated annual increase in the rotational angle of leaning is about 0.09^{o}. Therefore it cannot be said that the building has reached its final settlement stage in the cause of this study. Summarily, the structural failure at this site is mainly as a result of the seasonal swells and shrinkages of the overburden (swelling active soil), frequent seepages of lavatory effluents and the waste liquids from the drainage paths and, the presence of structural features such as syncline and dipping subsurface. Table 4 shows the summary of the subsurface conditions at the study site and, the potential cause and failure mechanism of the building.

Table 4: Summary of the Subsurface Conditions at the Study Sites and their Potential Effect on the Buildings' Foundation.

	Interpreted Subsurface Condition	Potential Effect on/ Failure Mechanism Of The Building
1	All season saturation of the subsurface due to seepages into the foundation depths at the drainage paths/lavatory section (at western side) of the building (Figures 4 and 5)	Weakness of the subsurface materials underlying the western side of the building more than that at the eastern side of the building resulting to the leaning towards its western side (Figures 10, 11, 12 and 13).
2	Significant contrast in the subsurface resistivity and p wave velocity (Figures 10, 11 and 13)	Differential subsurface consolidation between the eastern and the western sides of the building's subsurface resulting to differential settlement of the building (Figures 10, 11, 12 and 13).
3	Significant swell–shrink movement at foundation depths due to the presence of expansive clay (Tables 3 and 2).	Severe foundation-based cracks at many parts of the building (Figure 2c).
4	Probable occurrence of dipping layer and anticline at depths beneath the building (Figures 10 and 12).	Decelerated settlement up-dip (at the eastern side of the building) while progressive settlement take place at the western side of the building (Figures 10 and 12).
5	Synclinal structure underlie the side at depth towards which the building lean (Figure 13).	Prolonged subsurface consolidation due to the thickness of clayey overburden at the western side of the building (Figure 13).

CONCLUSIONS

Based on the investigation in the foregoing, the inversion resistivity models of the profiles show that the foundation depths of the site are predominantly characterized by sandy clayey and clayey soils. The peculiar tilting of the building is invariably attributable to the consistent swelling and shrinkages of its clayey subsurface. Therefore the most probable major causes of the failure at the study site are the occurrence of active clay at shallow depths, low strength of intact rocks and some underlying geological structures. Apart from the seasonal consequence of the swell-shrink occurrences, the frequent seepages through the foundation based cracks at the outer walls of the lavatory most likely, have contributed weakness of the western side of the building.

The dipping subsurface, occurrence of anticline and synclinal structure which is delineated at the site, most likely have also contributed to the occurrence of the differential settlement. The severe structural cracks and uneven settlements of the structures might have occurred because of the excessive ground movement. Dry or less saturated subsoil usually enhance consolidation but if the soil is consistently saturated, it becomes very weak and will invariably amount to weak supports to the structures which they underlie thereby putting them at risk. Since progressive settlement is noticed in the recent past few years, the superstructure most likely, is undergoing an *irreversible consolidation settlement*. It is therefore recommended that builders in Nigeria and other places that share similar geology should take decisive measure about the foundation works intended on every known, and suspected active subsoil. It may therefore be required of the geoscientists to provide results of both physical tests on soil and rock samples, and the chemical analysis of the soil in order to help builders to determine the possible deleterious effects on the foundation structure.

There is also need for the classification of soils and rocks, implementation and evaluation of the Standard Procedure for Codes of Practice in Nigeria. Frequent study and continuous geophysical data appraisal, in whatever procedure, should also be adopted. This however will help land users to keep vital information about the level of strength/weakness of subsurface materials, deep weathering of soil rock formation and sub-artesian water pressure. It is also recommended that for the purpose of the nation building in Nigeria and some developing countries having similar challenge, laws meant for the curbing and controlling indiscriminate erection of high-rise buildings without carrying out proper and detailed geophysical/geotechnical

investigation should be properly enforced. By so doing, money and property are saved and, lives of building occupants will be kept from the risks therein.

ACKNOWLEDGEMENTS

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REFERENCES

1. Adanu, E.A. and Schneider, M. 1988. "Hydrogeology and Aquifer Simulation of the Basement Rocks of Kaduna-Zaria Area, Northern Nigeria". *Adv. Water Resource.* 11.44-47.

2. Alagbe, S.A. 2002. "Groundwater Resources of River Kangimi Basin, North-Central, Nigeria". *Environmental Geology,* 42:404-413.

3. Burland, J.B., Broms, B.B., and De Mello, V. 1977. "Behaiviour of Foundation and Structures": In: *Procedings of The 9th International Conference of Soil Mechanics.* Session 2. Tokyo, Japan.

4. Chilton, P.J. and Smith-Carrington, A.K. 1984. "Characteristics of Weathered Basement in Malawi in Relation to Rural water Supplies". In: *Challenges in African Hydrology and Water Resourses.* D.E. Wallings, S.S.D. Foster, and P. Wurzel (editors). 57-72. *Proceedings of the Harrare Symposium, IAHS Publication* No. 144.

5. Clark, L. 1985. "Groundwater Abstraction from Basement Complex Areas". In: Greenbaum 1992, Okereke, C. S., Esu, E. O. and Edet, A. E. "Groundwater Investigations: Experiences in parts of Cross River State, SE Nigeria". *WATER RESOURCES, Journal of Nigeria Association of Hydrogeologists*. 4(1&2):10-20.

6. deGroot-Hedlin, C. and Constable, S.C. 1996. "Occam's Inversion to Generate Smooth, Two-Dimensional Models from Magnetotelluric Data". *Geophysics,* 55:1613-1624.

7. Du Preez, J.W. 1956. "Origin, Classification and Distribution of Nigerian Laterite". *GSN Report* No. 810.

8. Edet, A. E., Teme, S.C., Okereke C.S., and Esu, E.O. 1994. "Lineament Analysis for Groundwater Exploration in Precambrian Oban Massif and Obudu Plateau, S.E. Nigeria". *Journal of Mining and Geology*. 30(1):87-95.

9. Edwards, L.S. 1977. "A Modified Pseudosection for Resistivity And Induced – Polarization". *Geophysics.* 42:1020 – 1036.

10. Gibbs H.J. and Holtz, W.G. 1956. "Engineering Properties of Expansive Clays" *Trans Am. Soc. Civ. Eng.* 121(1):2814.

11. Graffith, D.H. and Barker R.D. 1993. "Two-Dimensional Resistivity Imaging and Modeling in Areas Of Complex Geology". *Journal of Applied Geophysics.* 29:211-226.

12. Grey, D.R.C., Chilton, P., Smith Carrington, A.K. and Wright, E.P. 1985. "The Expanding Role of Hydrogeologists in the Provision of Village Water Supplies: An African perspective". *The Quarterly Journal of Engineering Geology.* 18(1):13-24.

13. Hydro Skill and Engineering Services, Kaduna, 2005. Files on Borehole Records in Ahmadu Bello University, Zaria, Nigeria. Estate Department, A.B.U., Zaria.

14. Ike, E.C. 1988. 'Late-stage Geological phenomena in the Zaria Basement Granites. A Review in the Precambrian Geology of Nigeria". Published by the *Geological Survey of Nigeria*. pp 83 – 89.

15. Jones, M.J. 1985. "The Weathered Zone Aquifers of the Basement Complex Areas of Africa". *The Quarterly Journal of Engineering Geology*.18: 35-46.

16. Koefoed, O. 1979. *Geosounding Principles 1: Resistivity Sounding Measurements*. Elesvier Science Publishing Company: Amsterdam, The Netherlands.

17. Loke, M.H. and Barker, R.D. 1996. "Rapid Least-Squares Inversion of Apparent Resistivity Pseudosections by a Quasi-Newton Method. *Geophysical Prospecting*. 44:131-152.

18. McCurry, P. 1970. "The Geology of the Zaria Sheet 102 S.W. and its Region". In: Mortimore, M.J. (Ed.). Department of Geography Occasional Paper, No.4. Ahmadu Bello University: Zaria, Nigeria.

19. Offodile, M.E. 1983. "The Occurrence and Exploitation of Groundwater in Nigerian Basement Rocks". *Journal of Mining and Goelogy*. 20(1&2):131-146.

20. Sasaki, Y.M 1992. “Resolution of Resistivity Tomography Inferred from Numerical Simulation”. *Geophysical Prospecting*. 40:453-464.

21. Sands, T.B. 2002. “Buildings Stability and Tree Growth for in Swelling London Clay-Implications for Pile Foundation Design”. www.agu.org .

22. Telford, W.M., Geldart, L.P., Sherif, R.E., and Keys, D.A. 1990. *Applied Geophysics. 2nd Edition.* Cambridge University Press: New York, NY.

23. Tim, C. 2002. “House Foundation. Ask the Builder, Nationality Syndicated Newspaper Columnists”. www.askthebuilder.com .

24. Tomlingson, M.J. and Boorman, R. 1999. *Foundation Design and Construction*. Longman Scientific and Technical: Singapore. 1- 125.

25. Wright, E.P. 1992. “The Hydrogeology of Crystalline Basement Aquifers in Africa”. In: E. P. Wright and W.G. Burgess (Eds). *The hydrogeology of crystalline Basement Aquifers in Africa.* Geological Society Special Publication No. 66:1-28.

26. Wright, J.B. and McCurry. P. 1970. “Geology of Zaria and its Region (sheet 102 SW)”. In: Mortimore M.J. (Ed.). “Zaria and its Region”. Occasional paper No. 4 Published in Department of Geology, Ahmadu Bello University: Zaria, Nigeria. 5-12.

27. Zeynal, A.E. and Re, 2003. “Engineering Characteristics and Environmental Impacts of the Expansive Ankara Clay, and Swelling Maps for SW and Central Parts of the Ankara (Turkey) Metropolitan Area”. *Environmental Geology. Spring Berlin/Heidelberg*. 44(8):977 – 992.

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