Application of Geophysical Imaging in Investigation of Structural Failure of Buildings: Case Study of Three Building Sites in Zaria Area, Northwestern Nigeria.

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ABSTRACT

Cracks on concrete and masonry walls could be bothersome for quality of life and for property claims. Diverse patterns of wall cracks, leaning, and differential settlement of three building structures in Zaria area, north central Nigeria were investigated using geophysical imaging technique. Seismic Refraction and Electrical Resistivity Imaging were integrally applied in the study. Hence the mechanisms of the failures, cracks' identity and classifications, patterns and sizes, based on their cause traced in the survey were accentuated. The results of the integrated geophysical imaging were provided to resolve some ambiguous questions raised by indigenous geoscientists and engineers over the prevalent structural failures.

(Keywords: structural cracks, settlement, failures, seismic refraction, electrical resistivity, tomography)

INTRODUCTION

Structural failure is said to have taken place when there are unacceptable differences between expected and observed performance of any structure. In many parts of the world, lives have been lost and casualties have been recorded due to structural failures. Common structural failures in the world today include the failures of bridges, dams and the failure of buildings, which is the most prominent of all. Records of such structural disasters are common in Western Canada, Colorado, Texas, Wyoming, India, Nigeria, Israel, South Africa, and to some extent South Australia, California, Utah, Nebraska and South Dakota most of which were associated with swelling clays (Blyth and de Freitas, 1988).

According to Blyth and Freitas (1988), the foundation of any structure is meant to transfer the load of the structure to the ground without causing the ground to respond with uneven and excessive movement. Building failures can be considered to have occurred in a component when that component can no longer be relied upon to fulfill its principal functions. Limited deflection in a floor which causes a certain amount of cracking and distortion in partitions could reasonably be considered as defects, whereas excessive deflection resulting in serious damage to partitions, ceilings and floor finishes could be classified as utter failure. Investigators and reporters of structural failures are not only expected to identify trends leading to structural safety problems but are also expected to suggest topics for critical research leading logical solution against the trend (Chapman, 2000).

Foundation cracks are evaluated based on their size and extent. The British Royal Institute of Chartered Surveyors (RICS) evaluated cracks and tilting of buildings based on the questions pointing to whether they are slight, isolated, moderate, severe, or very severe cracks. Other questions used for evaluation are based on whether there are multiple small cracks, leaning, shifting (creep and crawl) which can be serious. Generally, cracks associated with displacement of original structural or mechanical components are considered to be significant (Donald and Cohen, 1998).

Most settling cracks on building walls are basically caused by either the differences in expansion and compression coefficients of construction materials, relative changes in the shapes and sizes of saturated soils or the dynamic earth. The amount, type and direction of foundation movement are commonly noted from the bulging of brick or masonry block. These in turn reveal the risk of vertical collapse or horizontal dislocation. The risk could be traced to the height of construction, material used for the building, site factor, earth loading or waterlog. Other factors include the seismic action, atmospheric extremes, or mere physical accidents. However, if cracks are old with no sign of continuing or recurrent movement, building inspectors accept monitoring rather than quickly recommending repairs (Tim, 2006).

The cause of rampant failure of building foundations due to subsurface movements giving rise to cracks or structural differential settlements is of great concern to geoscientists. There is need to distinguish between a continuing movement, which is often more likely to be a problem, and single eventual movements, which may not require repair depending on the extent of damage.

Adequate insight on the types, and patterns or foundation-based cracks and their evaluation is vital as one considers the geological and geophysical basis to buildings' failures. Therefore this investigation is therefore aimed at reviewing diverse cracks patterns and failure mechanisms of some buildings in Zaria area, northwestern Nigeria. Two geophysical imaging techniques were applied in the investigation with the aid of state-of-the art geophysical equipment as an arm of an on-going multidisciplinary survey on buildings' foundation failures in Zaria area.

BACKGROUND OF THE STUDY

Foundation cracks on buildings occur as a result of differential movement on the building. In most cases, serious damages caused by cracks on building can be safely repaired when these differential movements stop. 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 foundation based failures (Tim, 2002).

Before the present study, some geological and geophysical works have been carried out in Zaria area yet, none of them considered the structural failure of some buildings in the area. Table 1 shows the summary of the previous geophysical investigations in Zaria area.

Presently, there are ongoing environmental geophysical surveys in the area which have included the investigation of structural failure of buildings, origin of some valleys, dam site investigations, pollution studies, and classification of Zaria rocks. The present study is therefore the first to address the structural failures using integrated geophysical technique. Seismic refraction tomography and Electrical resistivity imaging techniques are simultaneously applied at three building sites.

Table 1: Summary of Some Previous Geophysical Studies in the Zaria Area.

Year of Study	Geoscientist(s)	Subject of Study	Inferences
1968	Ososami	vertical electrical sounding for ground water potential	Depth to the aquifer in the area varied from about 1m to about 30m. demarcation of the boundary between the weathered basement and the fresh basement
1978	Baimba	resistivity and seismic refraction studies for ground water exploration	basement complex generally forms poor source of ground water
1979	Onugba	detailed resistivity and seismic refraction survey of Kimberlite pipe area	correlation of seismic velocities of shallow structure with resistivity profiling results, has shown close agreement between the regions of anomalous
1985	Olufemi,	Resistivity survey	Siting of Borehole
1990	Ogah	applied the beam forming techniques to enhance low quality seismic refraction data at Kubanni drainage in the area	beam forming technique adequate for extracting useful information from low quality seismic refraction record
1990	Shemang	Resistivity survey	weathered and fractured basement constitute the main aquifer components
1991	Hassan, *et al.*	Geo-electrical investigation	Bedrock undulating

SIGNIFICANCE OF THE STUDY

The study area lies within 7^0 35′ 17″E and 7^0 41′ 17″E longitude, and 11^0 7′ 50″N and 11^0 11′ 22″N latitudes on the National grid of Nigeria and at an elevation of about 670 m above the mean sea level. It lies on a dissected portion of the Zaria–Kano plains. The plains are an extensive peneplane developed on the crystalline rocks of the Nigerian Basement Complex. Residual granite inselbergs, the largest of which is the Kufena Hill, provides the main relief in Zaria area. The area has a tropical continental climate with distinct wet and dry seasons. Three of affected buildings were selected for study from the area. Table 2 shows the locations of the three buildings' sites selected for study as measured with the aid of a geo-positioning system.

Site one's building has been under maintenance with masonry patches which have not provided a permanent solution to the problem. Although some of the cracks observed were not originated from the foundation but from the roof owing to poor masonry work. The most prominent crack is a major vertical cracks which divides the building at its centre in NE-SW direction (Figure 1).

Site 2 of the study area is a two bedroom bungalow. For over one decade, the building has been undergoing repairs annually as reported by the occupant of the building. The most prominent crack is a vertical one which divides the building almost into two trending east-west direction and originating from the foundation where its occurrence is widest (Figure 2). Preliminary survey of the site shows that the building's site is principally characterized by clayey top soil.

Table 2: Locations of the Buildings' Sites of the Study Area Selected for the Study.

Site	Longitude	Latitude	Height above M.S.L.	Topography
1	7^0 39′ 48"E to 7^0 39′ 50"E,	11^0 08′ 56"N to 11^0 08′ 57"N	665 m	Sloppy
2	7^0 38′ 19"E to 7^0 38′ 25"E,	11^0 08′ 58"N to 11^0 08′ 04"	667 m	Relatively flat Gentle slope
3	7^0 38′ 55"E to 7^0 38′ 56"E,	11^0 09′ 16"N to 11^0 09′ 18"N	668 m	Flat

(G.P.S. measurement: Field work)

Figure 1: Some Views of Cracks on Site 1 Building.

Figure 2: View of Some Cracks on Site 2 Building.

Site 3 of the study area is a university students' hostel block. It is a three storey building consisting of about 48 rooms. Outstandingly, the building settlement was observed to be leaning in West-East direction of the site at the angle of about 5.50^0 and its deepest settlement depth is about 0.675 m (Figure 3). Presently, the building is considered unsafe and dangerous for habitation hence evacuated. Geophysical investigation is therefore required necessary in order to map the subsurface structures underlying the buildings having structural failure.

METHODOLOGY

Geophysical methods usually measure the changes in the physical characteristics of soils and rocks. In building site investigation, geophysical methods such as electrical resistivity, gravimetric, magnetic seismic refraction and reflection, borehole logging, side scan, sonar and ground penetration radar are applicable.

Although geophysical methods do not give a direct quantitative data on shear strength compressibility or particle size distribution, measurement such as seismic velocity can be helpful in assessing the effect of weathering and discontinuities on the compressibility of soil and rock masses (Tomlingson and Boorman, 1999). Seismic refraction tomography (Kayal, 2003) and electrical resistivity Imaging were used for the investigation of the building sites. Refraction tomography performs well in many situations where the conventional methods fail especially in areas of complex geology (Jacob *et. al.*, 2006).

On the other hand, electrical resistivity tomography has also been found to be a time saving and more accurate subsurface modeling technique. 2D survey measures the resistivity changes both in the vertical direction, as well as in the horizontal direction along common survey line at the same time. 2D electrical imaging doesn't only give more accurate results and save time, it is also cost effective. While the 1-D resistivity sounding surveys may involve about 10 to 20 readings, 2-D imaging surveys involve about 100 to 1000 measurements.

Figure 3: Danger of Diagonal Cracks, Horizontal Cracks, and Angle of Leaning (Site 3).

Table 3: Summary of the Observation on the Structural Defects and Failure of the Buildings

Site	Building under Study	Defect	Approximate Crack Width (mm)	Description Of Typical Damage	Degree Of Damage	Required Repair
1	One storey (Residential)	Numerous cracks and differential settlement	4-17	Serious vertical and few diagonal cracks	A major crack divides the building into two from foundation: **Degree is Moderate**	Requires some opening up and masonry patches
2	Bungalow (Residential)	Several moderate cracks and few large cracks and breakages	16-35	Vertical and diagonal cracks prominent and single major horizontal crack	Walls lean badly, windows broken with distortion, danger of instability: **Degree is very severe**	Requires a major repair job involving partial rebuilding.
3	Three Storey (Students' Hostel)	Numerous cracks and leaning of the entire building	13 -24	Obvious occurrence of vertical, diagonal and horizontal cracks on most parts of the buildings' walls	Walls learning and bulging noticeably About 6.0 degree leaning angle, several diagonal cracks, a dangerous horizontal crack: **Degree is severe**	Requires extensive repair work involving breaking out and replacing sections of walls.

The two imaging techniques used in this survey are non-intrusive and non-destructive. Both methods are useful in the exploration for water, sand, gravel and in engineering/construction site investigation. The difference between the two methods is based on their differences in the physical property they measure and their associated parameter. While the SRT which measures the velocity or the elastic moduli of earth material in which travel times waves is the measured parameter, electrical imaging is concerned with the measurement of conductivity or resistivity of the earth.

Information obtained from any type of tomography is meant to infer the internal structure of the three-dimensional object after a sufficient interpretation. Seismic refraction involves several (detailed) shots along a profile line. Therefore, in the acquisition of the tomography data, shots are taken at each geophone point. The multiple shot points along a survey profile will provide greater data coverage for analysis and aids in generating a more accurate model so that the processed data which consist of direct-arrival travel times and seismic ray tomography will give a high resolution 2-D p-wave velocity tomogram.

The electrical imaging or electrical tomography is a survey technique recently developed for the investigation of areas of complex geology where the use of resistivity sounding and other techniques are unsuitable (Griffiths and Barker 1993). It involves measuring a series of constant separation traverses with the electrode spacing being increased with each successive traverse. Since increasing separation leads to greater depth penetration, the measured apparent resistivities may be used to construct a vertical contoured section displaying the variation of resistivity both laterally and vertically over the section. The 2-D electrical imaging is one geophysical development in recent years which can map even the areas with moderately complex geology (Griffiths and Barker, 1993).

FIELD PROCEDURE AND INTERPRETATION

Along 24 profile lines laid at each of the buildings vicinity, two-dimensional electrical resistivity tomography (ERT) and seismic refraction tomography (SRT) were applied in the study of the subsurface structures around the building site. In the electrical imaging survey, 42 steel electrodes were used. It was ensured that the ground surface was amenable to the electrode insertion. Terrameter SAS 4000 aided with its auto-electrode selector ES464 was used for the data acquisition. Wenner 32SX protocol (continuous vertical electrical sounding with two cables) was adopted for the field technique using electrode spacing ranging between 2.5 m and 5.0 m depending on each profile’s length. In the seismic refraction survey, 24 geophones were used at spacing of 5.0 m. Measurements were made using an ABEM Seismograph (Terraloc Mk 6) and shots were taken at each geophone position in order to ensure adequate scanning of the subsurface.

The electrical resistivity and seismic refraction tomography data were processed using inversion routine software packages. Resistivity data was processed using RES 2DINV software which displays a 2-dimensional colour image of the subsurface showing both vertical and lateral changes in ground resistivity. The data processing requires no previous knowledge of the subsurface; however, the initial-guess model is constructed directly from the field measurements.

Both standard and robust constraints of the least square inversion were applied (Claerbout and Muir, 1973). The pseudosections of the measured and calculated apparent resistivity were first displayed to show agreement; these were followed by the inverted resistivity models for profiles. The raw data of the seismic refraction tomography survey was downloaded from the seismograph and processed using REFLEX-W software package. First arrivals were picked from wiggle mode of seismic signal for each shot along the profiles. The arrival times were assigned to layers and models were generated. Typical of the inversion tomograms for both resistivity and seismic surveys were displayed after the data processing (Figures 4, 5 and 6). The tomograms obtained from the two methods at common profile show structural resemblance.

DISCUSSION

The building selected from site 1 is located very close to one of the minor valleys in the area. The zone directly beneath the major crack at the site has relatively higher p-wave velocity than its lateral surrounding at the front side of the building. This suggests that there are consolidation or compaction contrasts underlying the building owing to variation in compressibility. The compressibility contrast within the sandy clayey zone is as a result of the high consistency of the soils which results to compaction and density contrasts. The building therefore exerts its bearing pressure since its construction was completed. The pressure being exerted by the building on the subsurface owing to its gross weight invariably results in a progressive consolidation settlement of the building. During this consolidation which usually follows after the ***immediate settlement***, one side gradually gets consolidated faster than the other thereby serving as a stronger support than its flanks.

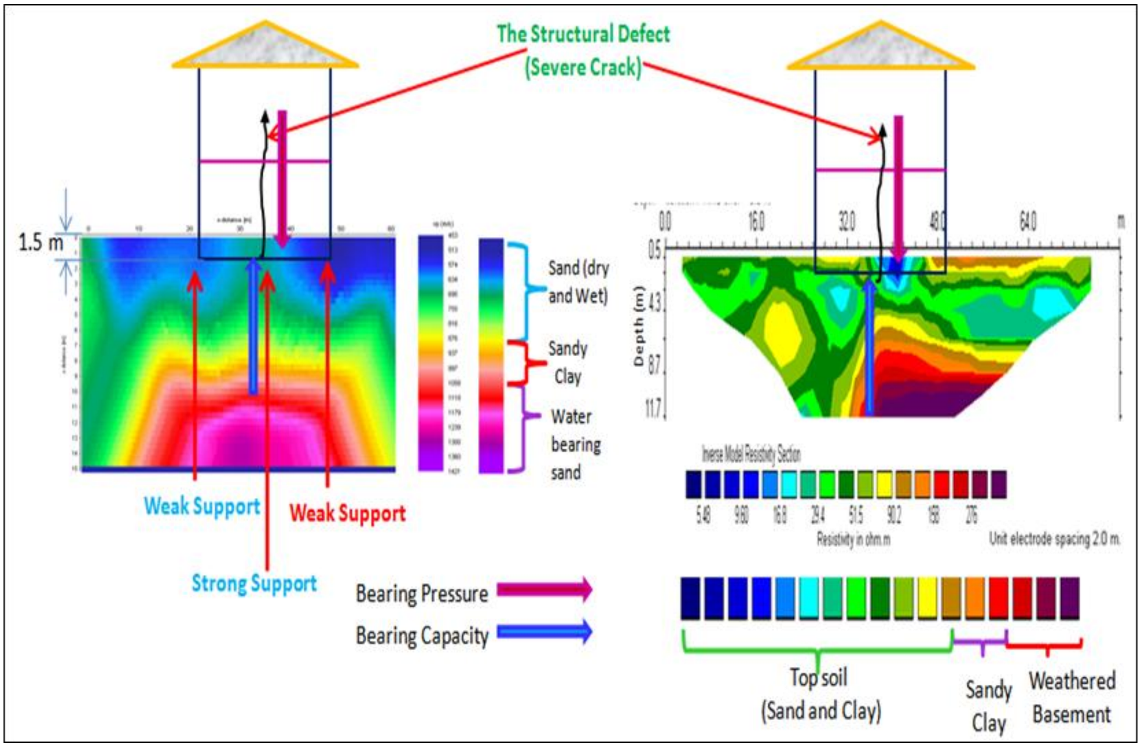

Figure 4: Seismic Refraction and Electrical Resistivity Tomograms and, Structural Failure Mechanism at Site 1.

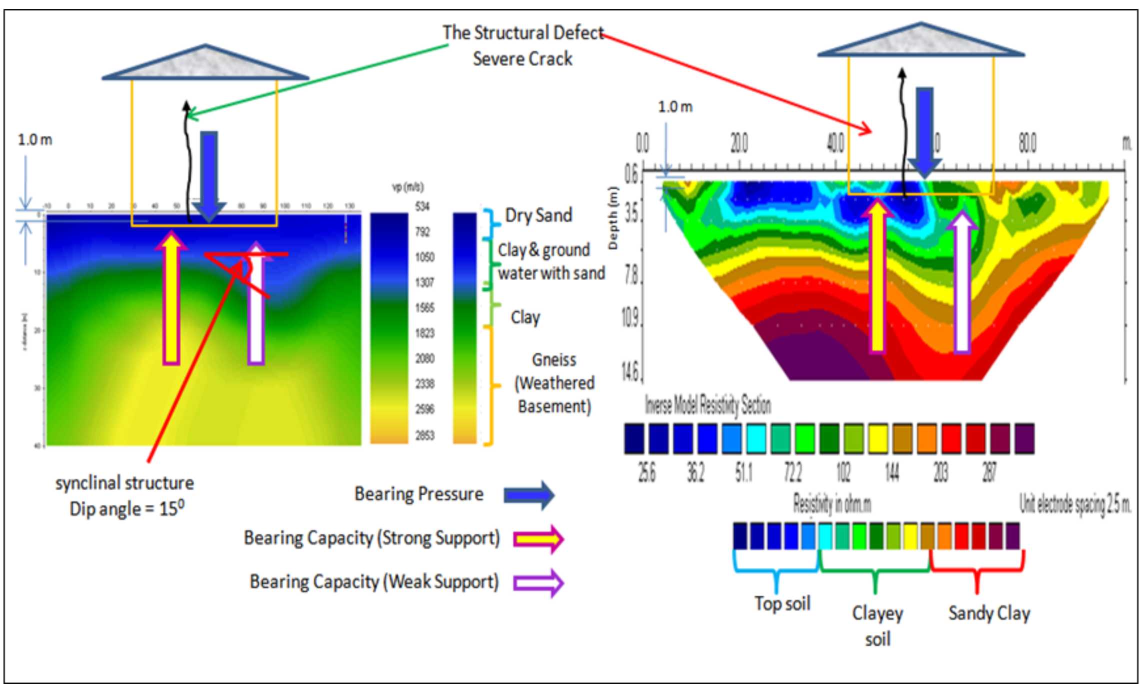

Figure 5: Seismic Refraction and Electrical Resistivity Tomograms and, Structural Failure Mechanism at Site 2.

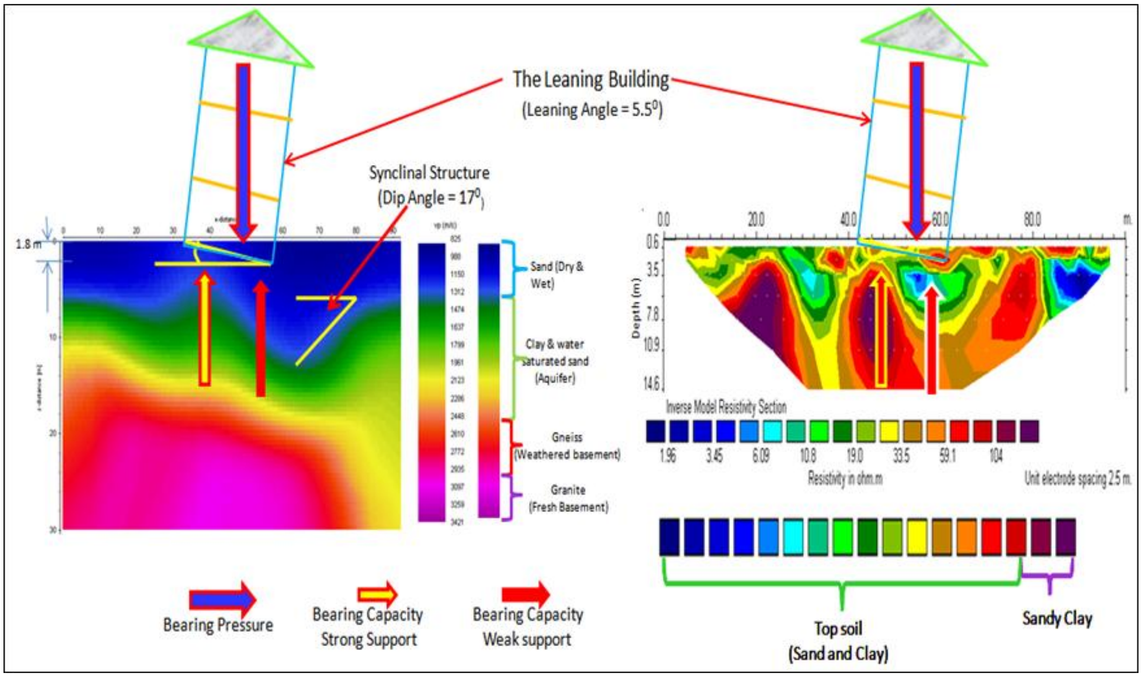

Figure 6: Seismic Refraction and Electrical Resistivity Tomograms and, Structural Failure Mechanism at Site 3.

This therefore suggests that consolidation or compression contrasts at the two sides might have contributed to the occurrence of the major and severe vertical cracks NW-SE on the building (Figure 4). Other probable reason for the structural defects on the site 1 building is the problem of swell and shrinkages of clayey soils. Seasonal variation in the level of saturation of clayey soils is expected to have given rise to the seasonal swelling and shrinkages of the building's subsurface.

The swell and shrink might have caused *ground movement* which invariably should have caused the defect (severe cracks) and the foundation instability of the building. The contrast between the shrinking clay and non-shrinking zone might have also contributed to the ground movement in the site which in turn, could bring about the risk on the structure. The electrical resistivity tomograms confirm structurally with the seismic refraction tomograms on many of the profiles mapped.

Results also show that the site 2 building is characterized by gentle EW dipping, prominent synclinal structures, fractured zones and clayey soil at shallow depths. While the overburden materials fill the fractured zones, their columns undergo ground movement by subsidence thereby could amount to uneven settlement at the foundation depths of the building. In other words, uneven stress distribution occurs at the foundation depths subsurface that is, one side of the structure to having a stronger support than the other side of it (Figure 5).

The site 3 tomograms also show significantly synclinal geologic structure at shallow depths and a gentle dipping layering. The dipping and the synclinal structure shown by the pseudosections of these profiles suggest that they could be the major basis for the structural failure of the site 3 building.

The weight of the superstructure which is three storey students' hostel building was initially supported by a seemingly stable subsurface at the end of its construction four decades ago must have undergone also differential settlement. Hence tomograms show that the front side of the building rests on a weaker support than the rear side of it (Figure 6). Table 4 shows the deductions from seismic refraction tomography and electrical resistivity imaging.

Table 4: Deductions from Seismic Refraction Tomography and Electrical Resistivity Imaging.

SITE	GEOPHYSICAL INTERPRETATION				ENGINEERING SIGNIFICANCE Compressibility (for 0-5 m depth range) (Pa^{-1}) $\pm$ 0.01 x 10^{-8})
	Lithology	**Thickness (m)**	***Borehole Logs (Control)***	***Interpretation of Tomograms***	
1	Overburden	11-17	Reddish Brown Top Soil, sand and clay	Sand, Clay and Sandy Clay	2.21797E-09 to 1.48677E-09
	Weathered Basement	12-30	Coarse Medium Grain Sand	Water Bearing Sand	
	Fresh Basement	18	____	Gneiss and Granite	
2	Overburden	3-21	Nil	Sand, Clay and Sandy Clay	6.23165E-10 to 1.45565E-10
	Weathered Basement	7-18	Nil	Water Bearing Sand	
	Fresh Basement	7	Nil	Gneiss and Granite	
3	Overburden	3-26	Reddish Brown Top Soil, sand and clay	Sand, Clay and Sandy Clay	4.17059E-10 to 1.45565E-10
	Weathered Basement	7-9	Coarse Medium Grain Sand	Water Bearing Sand	
	Fresh Basement	19	___	Gneiss and Granite	

CONCLUSIONS AND RECOMMENDATION

A reasonably confident guess about the cause of foundation movement by geoscientists and engineers helps in setting the specific maintenance to reduce further damage buildings. Soil tests by Geotechnical and soil Engineers helps to ensure the capacity of the soil support buildings. It is necessary to consider the pros and cons of each foundation type. They should be considered with respect to the site and the building height in order to make correct or adequate ***choice of foundation.***

Most structural problems can be avoided by proper design and planning. But if structural failures have been common for a long time, and sometimes are costly to handle properly. Hence, the present geophysical investigation at the building sites is of paramount importance. Confidence limit on such results is usually low when one method is applied to locate and characterize the subsurface features of a study site. However based on statistical analysis, when integrated geophysical methods are used, the confidence limit improves (Egwuonwu *et. al.,* 2009).

The use of sufficient and redundant data size in integrated geophysical investigation improves the confidence limit on the data and its interpretation. This improves the quality of results and reach conclusion based on plausible interpretations. The multidimensional modeling applied in this study shows that geophysical methods can be brought closer to their theoretical resolving power. Seismic refraction and electrical resistivity imaging has integrally mapped the near-surface targets have shown a strong positive correlation of tomographic micro-models. The strong positive correlation for most of the profiles in the study has provided plausible interpretations. Conclusions are made of the subsurface when geophysical methods are combined. Integrated geophysical technique applied in this paper can be equally be applied at other areas which share similar geology with the area under study.

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REFERENCES

1. ABEM Instrument AB. 1994. "Terrameter SAS4000 LUND Imaging System, Instruction Manual".

2. Baimba, A.B. 1978. "Resistivity and Refraction Seismic Methods for Groundwater Exploration at Zango, Kaduna State". Unpublished M.Sc. Thesis. Ahmadu Bello University, Zaria.

3. Blyth, F.G.H. and de Freitas, M.D. 1988. *A Geology for Engineers*. Butler and Tannar, Ltd. Frome and London: London, UK. 292-293.

4. Chapman, J.C. 2000. "Learning From Failures". Chapman Associates/Imperial College of Science, Technology and Medicine. 78(9):23-24. In *Assessment Of Building Failures In Nigeria: Lagos And Ibadan Case Study.* Ayininuola, G.M. and Olalusi, O.O. Department of Civil Engineering, University of Ibadan: Ibadan, Nigeria.

5. Donald, V. and Cohen. P.E. 1998 "Inspecting Block Foundation". American Society of Home Inspectors ASH. Reporter. December, 1998.

6. Egwuonwu, G.N., I.B. Osazuwa, and S.O. Ibe. 2009. "Spearman's Rank Correlation of Two Methods in Integrated Geophysical Investigation". *Pacific Journal of Science and Technology*. 10(2):693-701.

7. 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.

8. Hassan, M., Ajayi, C.O., and Ojo, S.B. 1991. "A Basement Structure Determined from Geoelectric Mapping of the Kubanni River Basin, Zaria". *Nigerian Journal of Physics*. 3:166-173.

9. Olufemi, R.O. 1985. "Hydrogeology of Jama'a Kubanni Area. (Zaria Sheet 102 Sw)". Unpublished B.Sc. Thesis. Ahmadu Bello University, Zaria: Zaria, Nigeria.

10. Onugba, A. 1979. "Detailed Resistivity and Seismic Refraction Survey Of Naseri/Kafur Kimberlitic Pipe Area, Near Malumfashi Kaduna State". Unpublished M.Sc. Thesis Ahmadu Bello University: Zaria, Nigeria.

11. Osasami, I.A. 1968. "Assessment of the Groundwater In The Kubani Valley". Unpublished M.Sc. Thesis. Ahmadu Bello University: Zaria, Nigeria.

12. Sands, T.B. 2002. "Buildings Stability and Tree Growth for in Swelling London Clay: Implications for Pile Foundation Design". www.agu.org.

13. Shemang, E.M. 1990. "Electrical Depth Soundings at Selected Well Sites within the Kubanni River Basin, Zaria". Unpublished M.Sc. Thesis. Dept. of Physics, Ahmadu Bello University: Zaria, Nigeria.

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

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