Geophysical and Geotechnical Investigation of the Origin of Structural Instabilities Shown on Some Low Rise Buildings in Zaria, North-Western Nigeria.

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ABSTRACT

Uneven settlements and foundation cracks due to differential stresses in the subsurface underlying some low rise buildings in Zaria is of significant concern to most Zaria-based geoscientists. This quest has necessitated geophysical and preliminary geotechnical study of the subsurface around three of such buildings in the municipal. Seismic Refraction Tomography was carried out on 24 profile lines laid around the buildings to probe depths in the range of 0-30 m. Also, Free Swell Test was carried out on 54 foundation soil samples collected within the depth range of 0-1.5 m in the vicinity of the buildings.

The investigation results show that the buildings were underlain by relatively weak and active overburden ranging from sandy clay to sandy alluvium having 0.2-2.7 free swell increase ratio. The clayey overburden forms data base in the knowledge of consistency, compression and compaction which play vital role in the definition of the bearing capacities of the foundation soils and rocks. Calculations based on the p-wave velocities in the area confirm that the weak overburden is characterized by relatively high compressibility in the range of 7.65686E-12 to 2.16208E-08 Pa^{-1}. The seismic refraction tomograms also clearly show that the overburden is underlain by undulated bedrock having N-S structural deformations and fracture pattern trending NE-SW.

Geological analogy suggests that the clayey overburden most likely originated from underlying weathered gneiss which formed typical soil horizons. The upper horizon of the clay profile resulted due to soil accumulation aided by transportation and windblown particles coupled with subsequent downward movement of the clay which has settled over weathered gneissic bedrock. Interpreted results also show that the clayey foundation depths, undulated nature of the bedrock and fracture patterns underlying the low rise buildings most probably led to the differential stresses on the buildings, the associated foundation-based cracks and their rotational tendencies. Furthermore, the interpretation reveals that the underlying undulations most probably originated from one of a two-phase structural deformation which resulted to folds, and that the fracture patterns underlying the buildings most probably originated due to vertical dissection and trans-current movements in the process of geologic time. These interpreted origins agree with those of previous regional investigations by earlier researchers in the area.

(Keywords: differential settlement, refraction tomography, free swell, structural deformation)

INTRODUCTION

Structural failures of buildings have resulted in the loss of lives, casualties, and loss of properties in many parts of the world. Nigeria is one of the countries where structural failures are relatively common (Blyth and de Freitas, 1988). Apart from atmospheric, accidental, and architectural causes of failure of buildings, the failure due to foundation problems vis-à-vis subsurface instabilities is now of great concern to indigenous geoscientists and engineers in Nigeria.

Ideally, the foundation of any building is meant to transfer the load of the structure to the ground without causing the ground to respond in uneven and excessive movement. Risk amount, type, and direction of foundation movement are commonly manifested in bulging of walls, vertical collapse or horizontal dislocation. These are traceable to either the height of the building, materials used for the building, site factor, seismic action, earth loading, atmospheric disaster, accident or access surface water (Tim, 2006). Foundation failure may be identified as an active one based on the age of the foundation, the speed of recurrent movement, speed of increment of cracks' length and width, speed of horizontal wall movement, an advancing wall tipping or leaning.

According to Robert (1996), most houses develop settlement cracks which are basically caused by either the differences in expansion and compression coefficients of the construction materials or by relative changes in the shapes and sizes of saturated soils in the dynamic earth. The diagnosis of foundation crack pattern aids adequate evaluation of foundation based cracks. Significant cracks occur when there is displacement of original structural or mechanical components of a building and these can be evaluated both in size and length (Donald and Cohen, 1998, Chapman, 2000). The British Royal Institute of Chartered Surveyors (BRICS, 1988) evaluate cracks and tilting of buildings based on whether they are slight, isolated, moderate, severe, very severe, multiples small cracks, whether there is leaning or shifting (creep/crawl) which can be very serious.

In situations of continuity or recurrence of movements or structural cracks, routine monitoring and repairs are usually recommended (Tim, 2006). Building Research Establishments have classified the degree of wall cracking ranging from negligible/ hairline cracks 0.1 – 1 mm) to the very severe cracks (> 25 mm) which requires major, partial or complete rebuilding (Tomlingson *et al.,* 1978).

Foundation-based cracks are commonly vertical, diagonal or horizontal. The vertical foundation cracks are often the least threat to the building than the diagonal and the horizontal patterns. However if there is significant vertical dislocation or sign of ongoing movement, soil scientific and geophysical investigation become urgent. However, vertical cracks which occur due to settlement quickly call for geophysical investigation (Edgar, 1980).

Diverse diagonal and steep crack patterns originate from building foundations are diagnosed based on their causes which are usually settlement, expansive clay soil, frost or close range existence of shrubs or trees. Sometimes, diagonal cracks are due to heave, clay soil, frost, shallow or absent footing, water problems or insufficient backfill (Edgar, 1980). Horizontal cracks have more immediate threatening of serious collapse than the vertical cracks. Short-term diagonal or vertical crack could be caused by settlement over sink holes, fill or organic debris which latter rots and settles (Edgar, 1980; Donald and Cohen, 1998).

Apart from poor quality construction, poor soil cause havoc within buildings and their outside walls. This is because some soils are very sensitive to moisture gain or loss. Some buildings develop foundation cracks shortly after they are built in the process of settling. Subsidence and heave caused by moisture content variation in clay soils is a major problem throughout the world, and may be made worse as global warming increases local climate variability (Lew, 1973).

The deformation behavior and fracture mechanisms of an intact rock are characterized by crack growth and deformation of the constituent grains. Although fractured rock can still carry load, most foundation-based structural failure are due to the deformation of a fractured rocks. Climatically driven soil moisture changes lead to swelling and shrinkage of clays. They also increase when trees are planted or removed close to existing buildings. However, when trees are growing close to buildings, the evaporative and transpirative needs of the tree roots can reduce soil water content especially when clays are involved. The clay shrinkage eventually leads to subsidence of the ground surface, thereby risking structural damage of superstructure. When trees are removed, the clay water content will increase the clay swelling pressures (Samuel and Cheney, 1974).

Geophysicists, geotechnologists, geologists, and building/soil engineering inspectors, can make a reasonably confident guess about the cause of foundation movement based on the results of investigations and suggest the capacity of the soil which can support the buildings of certain load limits (Zeynal and Re, 2003; Sands, 2006). Figure 1 shows some views of structural cracks on one of the buildings investigated. The main thrust of this paper is therefore to trace the origin of structures causative to the structural failure of some building in Samaru area, in Zaria based on geophysical and geotechnical interpretations.

Figure 1: Some Views of Cracks on one of the Buildings (Site 2).

THE GEOLOGICAL SETTING OF SAMARU AREA, ZARIA

Samaru area of Zaria is bounded approximately by 7°30´N and 7°40´E longitude and 11°08´ and 11°08´ latitude on an elevation of about 670 m above mean sea level. It occurs within a dissected portion of the Zaria–Kano plains which is an extensive peneplain developed on the crystalline rocks of the Nigerian Basement Complex. Residual granite inselbergs, the largest of which is called Kufena Hill, provides the main relief in Zaria.

The area has a tropical continental climate with distinct wet and dry seasons (Hore 1970). In Zaria, the mean daily minimum temperature is about 13^{o}C while diurnal temperature ranges from about 02^{o}C-04^{o}C. The Zaria crystalline rocks are part of the Nigerian basement complex that covers mostly the western half of the country which is related to the rest of West African basement (Oyawoye 1965, Mc Curry 1975, Truswell and Cope 1963). The basement is partly due to the whole region being involved in Pan-African orogenic event and has imposed a N-S structural grain upon the rock units.

The main lithological units in Zaria are granites and gneisses with other minor rock types such as schist and quartzites. In Samaru particularly, granitic intrusions form part of Zaria Batholith occupying some parts of Zaria while outcrops of the gneiss are exposed as low pavements, found mostly in the stream valleys of major rivers namely the Kubanni and the Galma rivers and their tributaries (Ike 1974).

The Zaria batholith comprises series of granites which have intruded the country rock gneisses. The structural elements common in the study area include veins, joints and faults which co-exist in an intimate relationship. Bala (2004) reported an average regolith thickness of 16 m on the Samaru main campus of Ahmadu Bello University, Zaria. While Adanu and Schneider (1988), reported that the weathered in the Zaria-Kaduna area rarely exceeds 50 m. An in-situ profile shows that the underlying weathered gneiss in the study area contains pieces of quartz and mica, windblown particles and a horizon of clay accumulation which illustrates the downward movement of clay (Klinkenberg, 1970).

METHODOLOGY

Basically, seismic refraction tomography was used in this study to delineate the subsurface structures causative the structural failure of the selected buildings. The travel time of seismic waves refracted at the interface between subsurface layers of different velocities is measured. Seismic energy is radiated from shot points on the ground surface. The waves travel directly through the upper layer to yield direct arrivals and downwards then laterally along a higher velocity layer as the refracted arrivals before returning to the surface. A linear spread of geophones spaced at regular intervals is used to detect the arrivals. In an ideal earth layers, a critically refracted ray path has travel time, *t, is* related to the depth *Z* of the refractor in a multi layer earth by;

$$t = \frac{X}{V_n} + \sum_{j=1}^{n-1} \frac{2Z \cos i_j}{V_j} \quad \textbf{(1)}$$

where *X* is the distance between the shot and geophone, *i* is the angle of incidence when the wave strikes the refractor which is the angle of refraction when the ray re-enters the first medium and V_n is the velocity of the wave in the n^{th} layer and ***j*** denotes the layer.

The character of the energy received is then used to infer the properties of the medium through which it is propagated. The p-wave velocities are easily obtained based on the seismic refraction data while s-wave velocity were calculated can be calculated for most soils and rocks using the ratio *Vp/Vs* which is given as:

$$V_p = 1.7 V_s \quad \textbf{(2)}$$

where V_p and V_s are the p-wave and s-wave velocities, respectively. This is determined by the value of Poisson's ratio for most consolidated materials which is about 0.25 (Keary and Brooks, 1996). Also in foundation studies, compressibility which is a dependent elastic constant of the subsurface of materials is a very essential parameter in the measurement of bearing strength. Compressibility, as derived by Salibury *et al,* (2003), after Birch, (1961), is given as:

$$\beta = \left(\rho V_p^2 - \frac{4}{3}\rho V_s^2\right)^{-1} \quad \textbf{(3)}$$

When tomography is applied to a seismic first arrival time data profile, it develops the best-fit velocity models by iteratively comparing different velocity structures with observed data to a degree of resolution specified by the model (Sandmeier, 2003). A 24-channels ABEM *Terraloc MK6 System* was used in the collection of seismic refraction data. Eight profiles were laid on the sides of each of the buildings under investigation.

Figures 2 a-c are the site plans showing the location of the buildings and profile lines laid around them, respectively. We oriented the profiles parallel to the four sides of the building so that the center of each spread was positioned at the zones where the most prominent cracks and breakages are shown on the walls of each of the buildings. While the major structural cracks trends NE-SW across the site 1's building, the major structural crack across the site 2's and 3's building trends in E-W and N-S directions, respectively.

The geophones' spacing used in the survey ranged between 1.25 m and 5.0 m depending on the spacing available around the building. Shots were taken at each geophone position to ensure high resolution in the seismic refraction tomography. Free swell test of soil sample collected at various locations around the buildings was carried out. The samples were collected at 0.0, 1.0 and 1.5 m respectively at those locations. The test was to supplement the interpretation which will be given to the seismic refraction results. Also, the compressibility of the formations at shallow depths was calculated to aid interpretation.

DATA PROCESSING AND RESULTS

The seismic refraction tomography data were processed using inversion routine software packages. The raw data of the seismic refraction tomography survey was imported from the instrument to the processing package and processed using REFLEX-W software package (Sandmeier, 2003). 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. The inversion tomograms of some of the seismic profile lines displayed after the data processing are shown in Figures 3-11. The results show that the interpreted seismic pseudosections show significant agreement with the borehole logs.

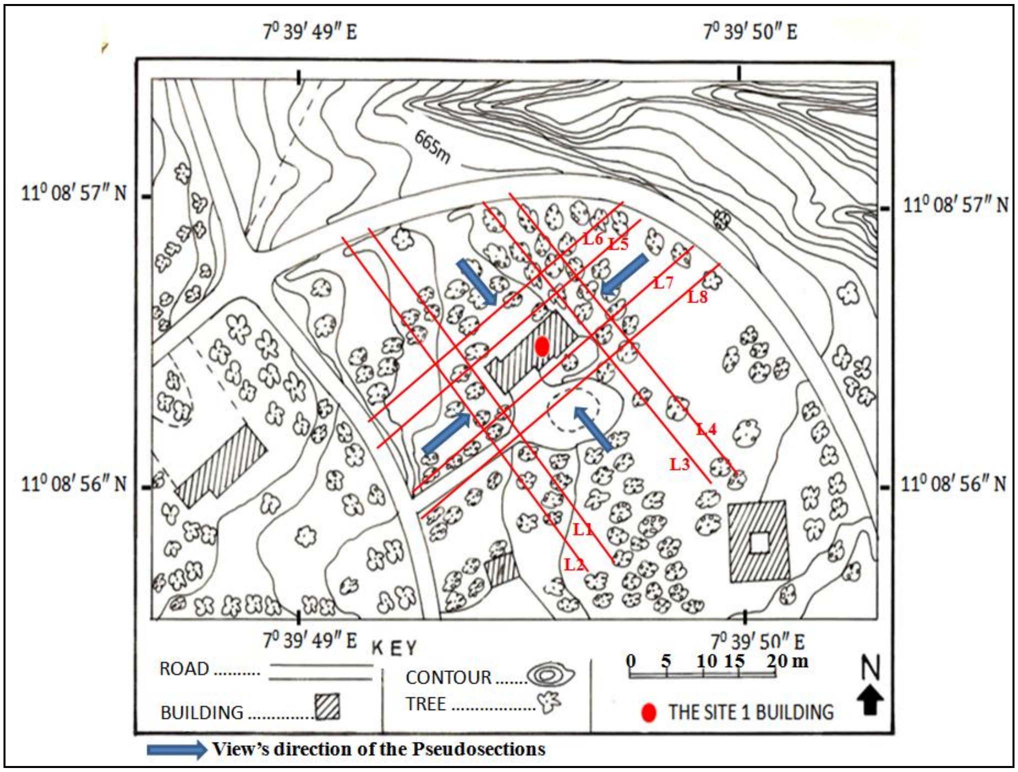

Figure 2a: Site Plan of Site 1.

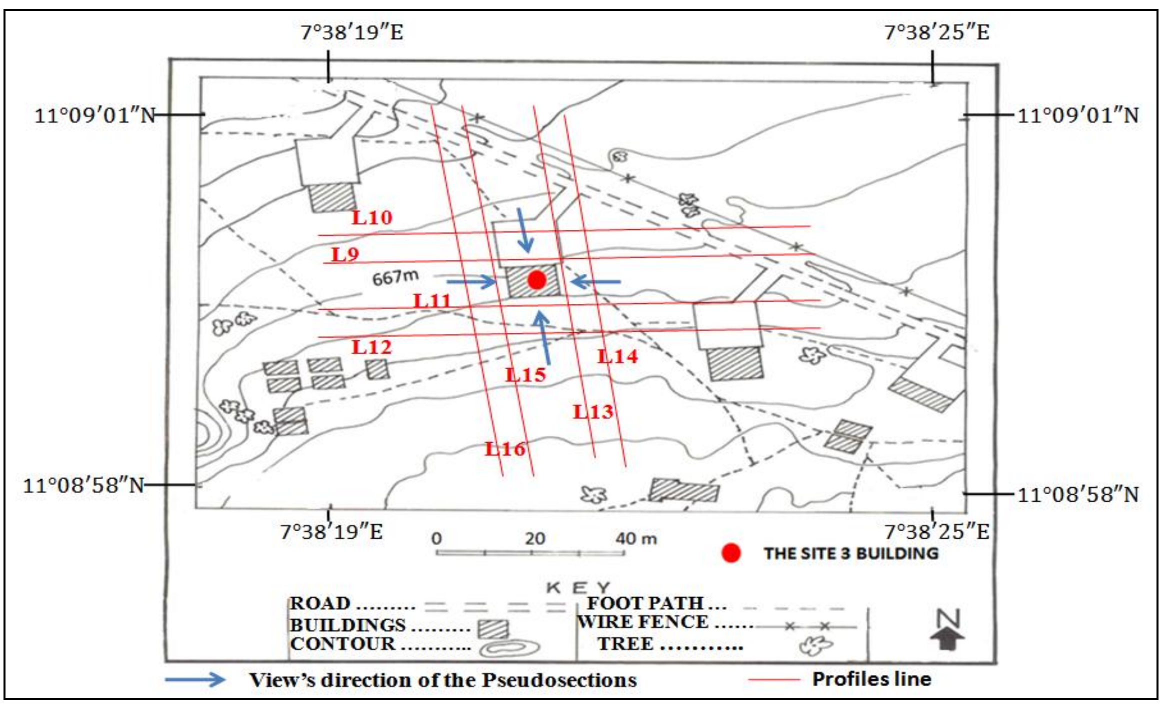

Figure 2b: Site Plan Site 2.

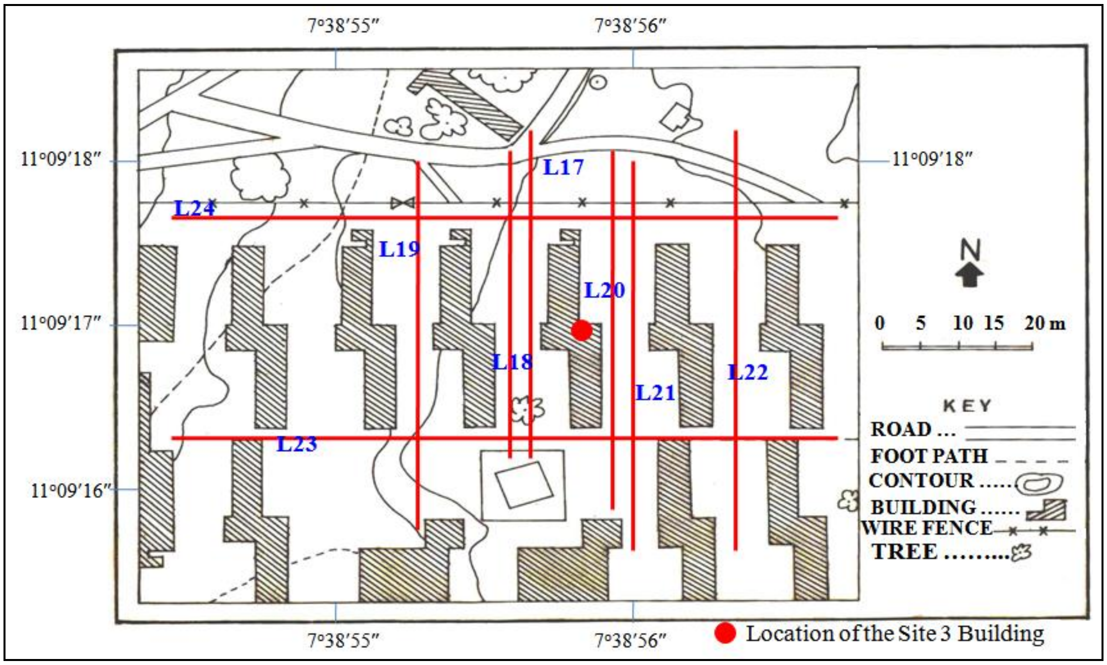

Figure 2c: Site Plan of Site 3.

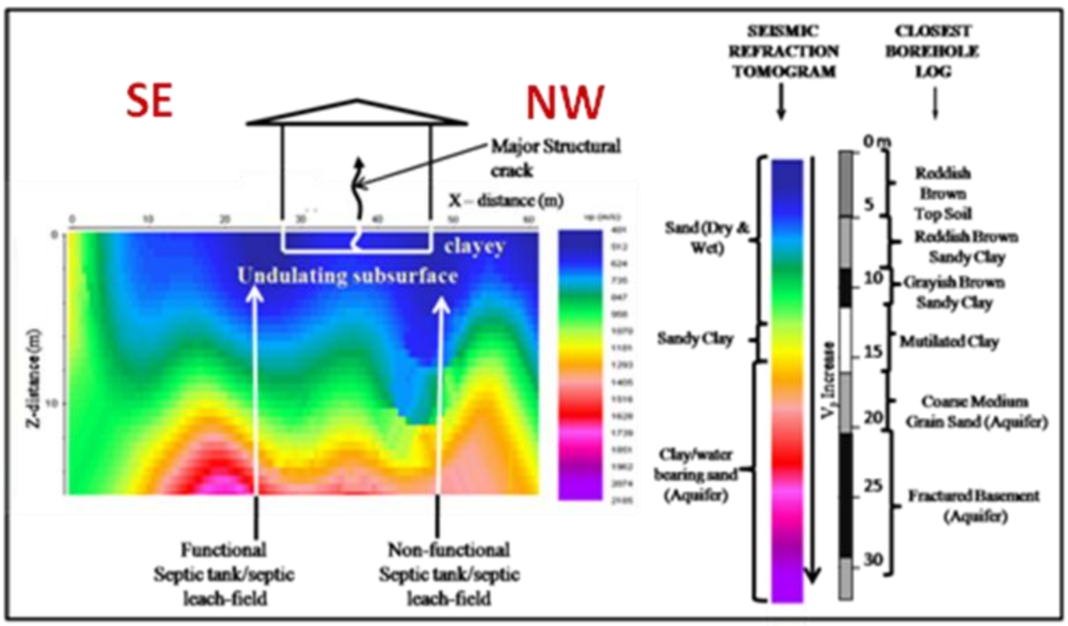

Figure 3: 2D Refraction Tomography Model Section of Profile L3 (Site 1).

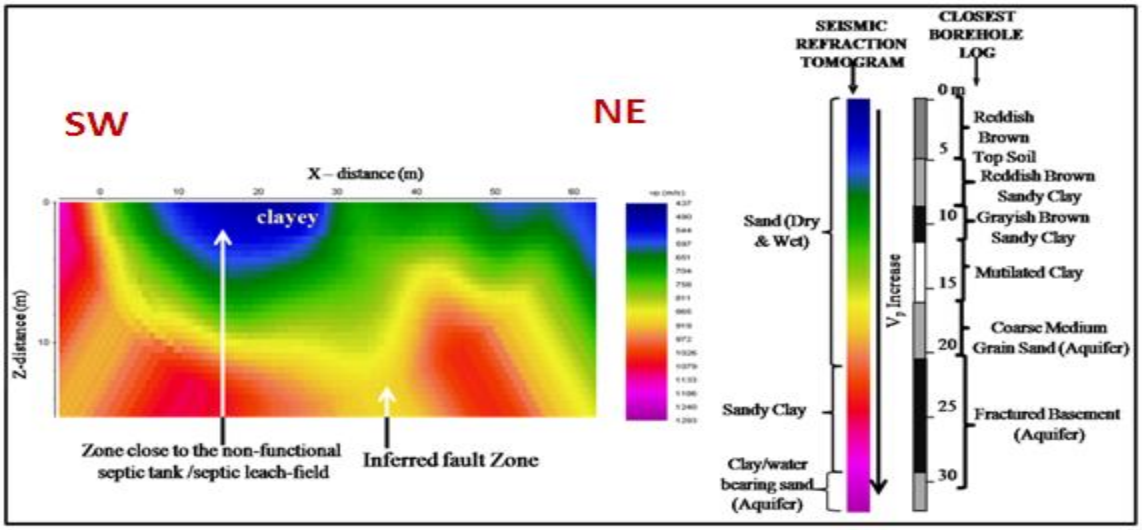

Figure 4: 2D Refraction Tomography Model Section of the Profile L5 (Site 1).

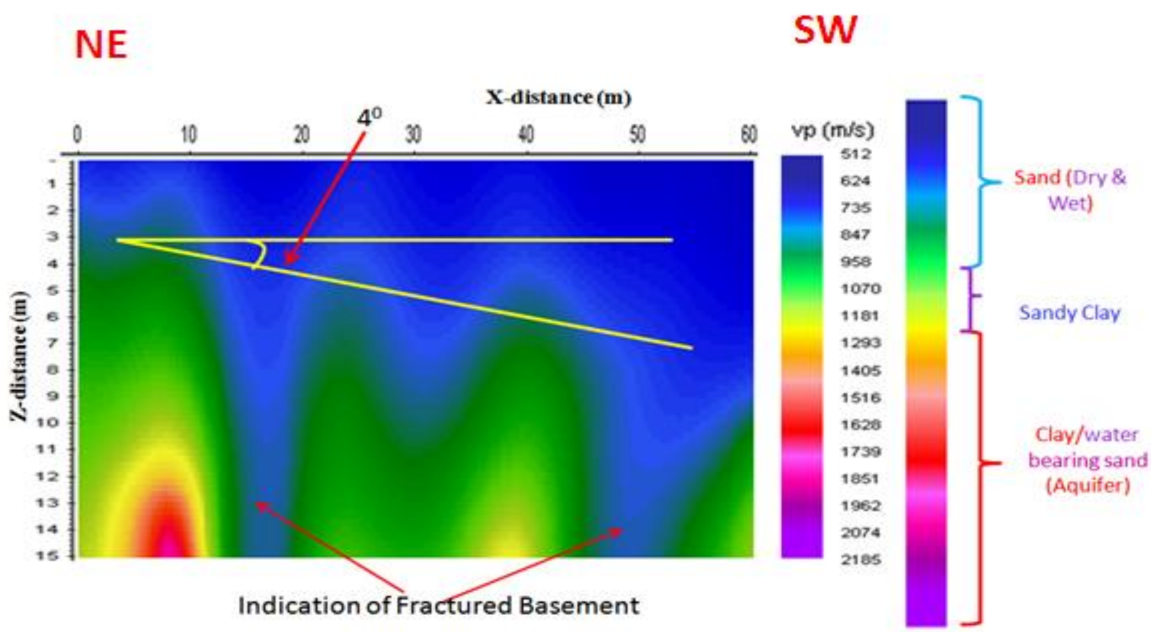

Figure 5: 2D Refraction Tomography Model Section of the Profile L8 (Site 1).

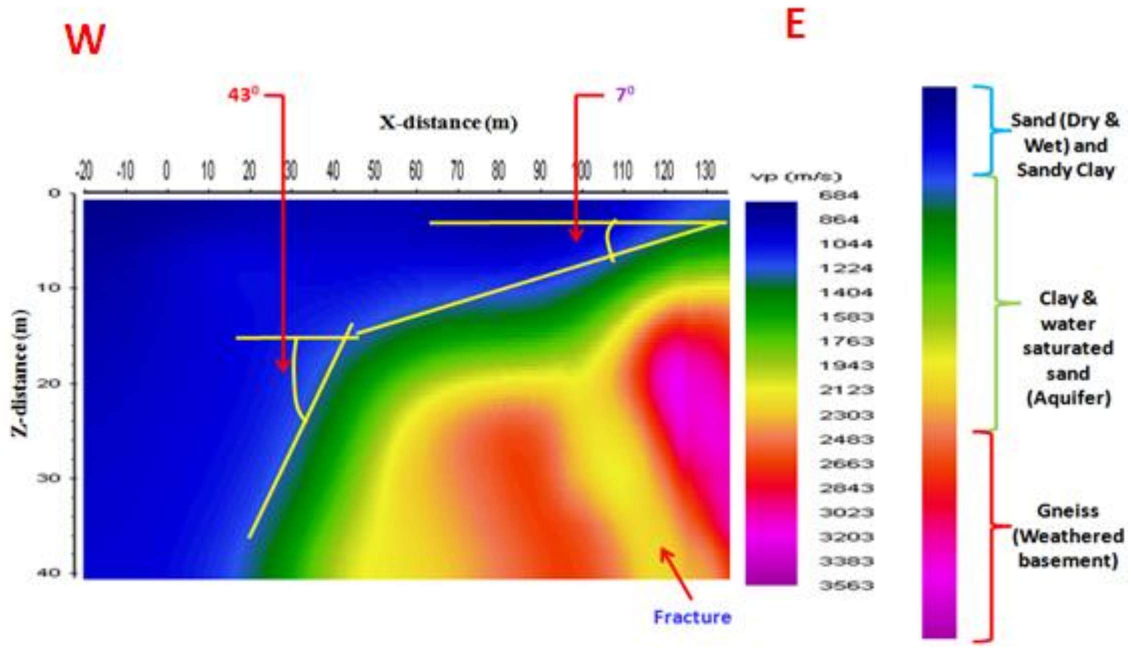

Figure 6: 2D Refraction Tomography Model Section of the Profile L12 (Site 2).

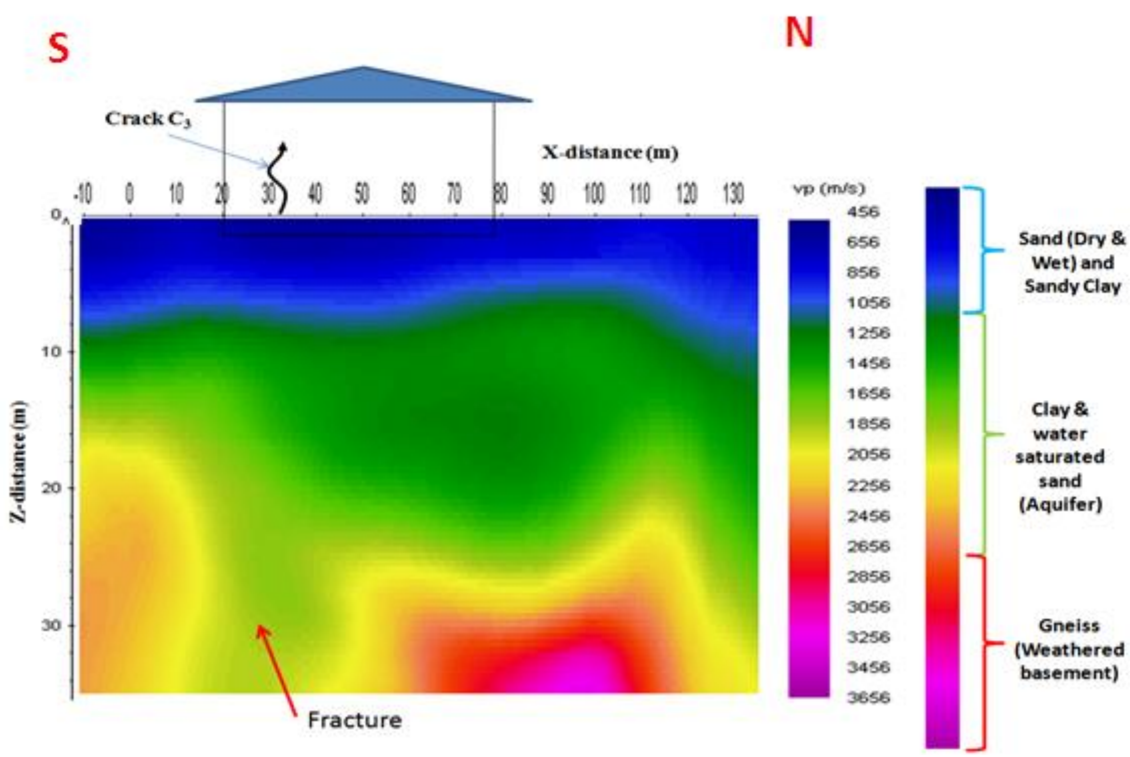

Figure 7: 2D Refraction Tomography Model Section of the Profile L13 (Site 2).

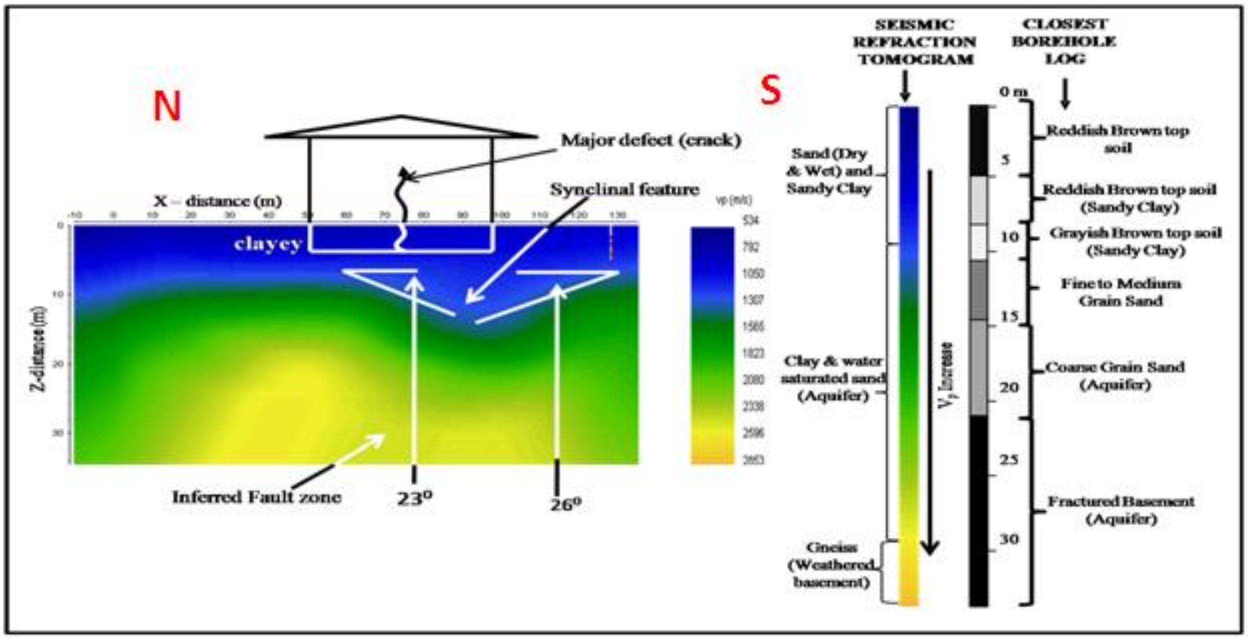

Figure 8: 2D Refraction Tomography Model Section of the Profile L15 (Site 2).

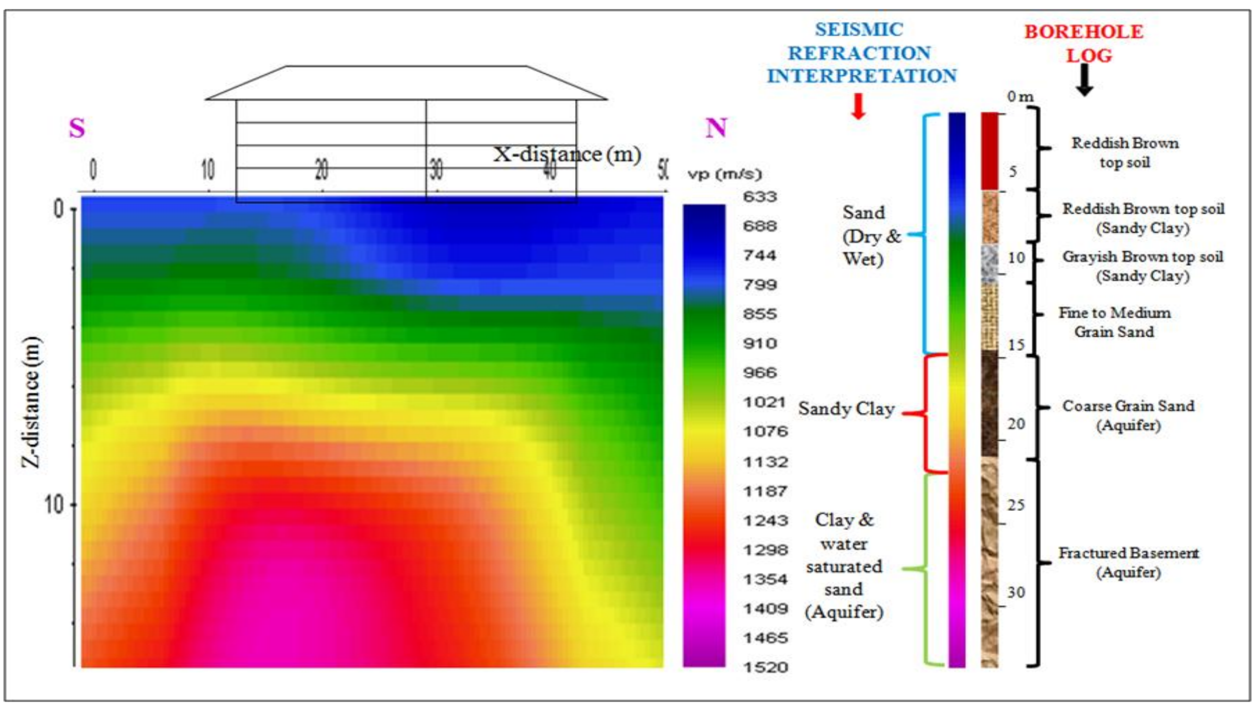

Figure 9: 2D Refraction Tomography Model Section of the Profile L19 (Site 3).

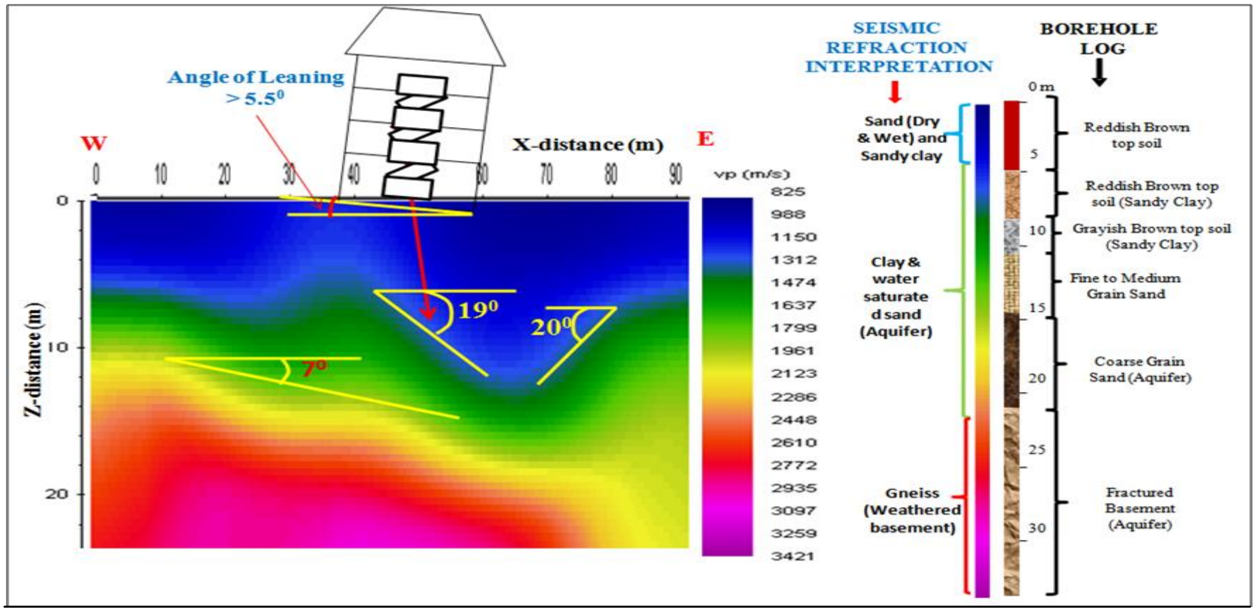

Figure10: 2D Refraction Tomography Model Section for Profile L23 (Site3).

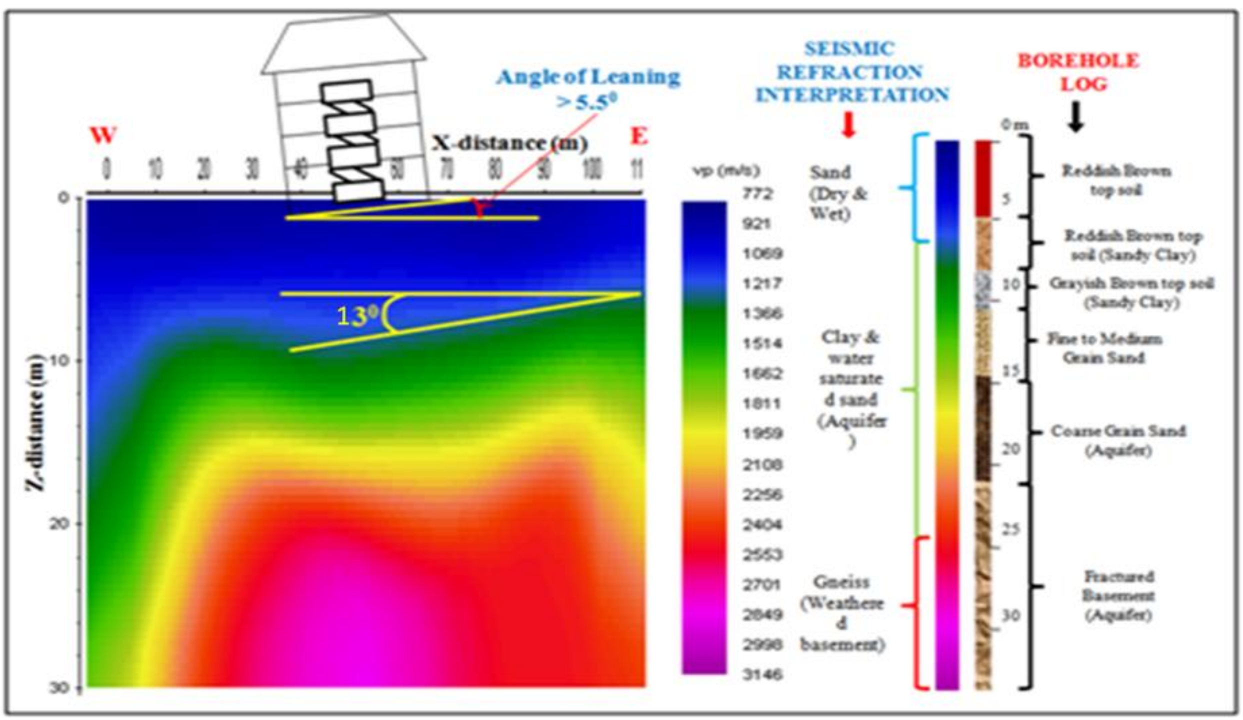

Figure 11: 2D Refraction Tomography Model Section for Profile L24 (Site 3).

The results of free swell test are shown in Table 1. The Table suggests that the range of the volume increase of the saturated clayey soils is 0.20-2.70 times of the original size. Table 2 shows the calculated compressibility of the various formations. The Table suggests that at shallow depths, the formations have high compressibility in the range of 7.65686E-12 to 2.16208E-08 Pa^{-1}.

DISCUSSIONS

The boreholes' logs and geology of the area were used as a control for the interpretation of all the seismic profiles laid in the study site. Results show that the seismic tomograms maps The results of the seismic tomograms show that the shallow depths in the study sites is predominantly characterized by clay and sandy clay soil (Figures 3-11).

Table 1: Results of the Free Swell Test on the Soil Samples Collected from Foundation Depths Around the Superstructures.

Side of the Building	Depth of Sample (m)	Free Swell (%)		
		Site 1	Site 2	Site 3
Front	0.00	150.0	121.0	165.0
,,	1.00	157.0	129.0	175.0
,,	1.50	130.0	121.0	140.0
,,	0.00	156.0	123.0	120.0
,,	1.00	148.0	109.0	195.0
,,	1.50	140.0	125.0	250.0
End A	0.00	226.0	122.0	185.0
,,	1.00	269.0	145.0	150.0
,,	1.50	258.0	156.0	175.0
Back	0.00	157.0	145.0	160.0
,,	1.00	143.0	144.0	125.0
,,	1.50	147.0	136.0	120.0
,,	0.00	154.0	225.0	145.0
,,	1.00	143.0	271.0	130.0
,,	1.50	145.0	268.0	135.0
End B	0.00	117.0	126.0	175.0
,,	1.00	119.0	156.0	170.0
,,	1.50	163.0	165.0	150.0
,,	1.50	147.0	136.0	120.0
,,	0.00	154.0	225.0	145.0

Table 2: Calculated Density and Compressibility for Interpreted Subsurface Materials at the Study Sites.

Interpreted Formation	Density ρ x 10^3 (Kgm^{-3}) $\pm$ 0.03	Average Depth Range (m)	Compressibility β x 10^{-10} (Pa^{-1}) $\pm$ 0.08		
			Site 1	Site 2	Site 3
Sand	5.42	0-8.0	2.22	6.23	4.17
Sandy Clay	6.12		2.16	2.83	2.84
Clay	8.29	8.0-22.0	1. 48	1.45	1.46
Water Bearing Sandy Clay	11.37		8.34	0.63	0.64
Consolidated Clay	18.91	22.0-30.0	1.32	0.19	0.19
Weathered Basement	25.47		1.42	0.11	.077
Allowable Total Foundation Pressure			< 0.04.5	< 1.6	< 13.1

Other structures delineated include fractures (Figures 4, 5, and 7), dipping layers (Figures 5, 6, 10, and 11), undulated basement (Figures 3, 5, and 10), and synclinal structures at shallow depths (Figures 8 and 10).

The clay and sandy clay soils delineated at shallow depths agree with Bala (2004) which holds that the low permeability in the weathered rocks in Zaria is due to the presence of clays and windblown particles and a horizon of clay accumulation which illustrated the downward movement of clay (Klinkenberg, 1970). The free swell test also suggests that the subsurface material has very high percentage of swell increase in the range of about 0.2-2.7% (Table 1).

According to Gibbs and Holtz (1956), soils having free swell values less than 50% are not likely to show expansive properties whereas the soils having free swell values of 100% or more are considered to be very active clay soils. Therefore the foundation soils in the vicinity of the buildings are most probably very active clay. Also, according to Sands (2002) and the Council for Geosciences, South Africa (2006), moisture changes lead to swelling and shrinkage of clays, affecting shallow foundation of buildings. Therefore the degree to which a soil expands or contracts is a critical cost factor, particularly for the foundations of important structures.

The unique climate of distinct wet and dry seasonal changes in Zaria most probably has contributed to seasonal swell-shrink movements of the superstructures. These creep-crawl movements, coupled with high compressibility of the foundation depths (7.65686E-12 to 2.16208E-08 Pa^{-1}) in Table 2 and the dipping shallow basement delineated at the study sites most probably have contributed to the differential settlement of the buildings.

The tomograms shows that the most of the fractures delineated are most probably trending either in NW–SE direction (Figures 4 and 5) or in and NE–SW direction (Figure 7). This agrees with Wright and McCurry (1970) who observed that most fractures in Zaria dissect the gneissic rocks into vertical joint surfaces in most outcrops of Area BZ around which the site 2 of this survey is located. Furthermore, McCurry (1970) and Ball, (1980) hold that these fractures have NW–SE and NE–SW patterns and had occurred as a result of the vertical dissection and trans-current movements in the basement complex.

It is also noticed that the synclinal structures delineated in this study in most probably trend in N-S direction (Figure 8) and E-W direction (Figure 10). This suggests that they have resulted from structural deformation trending in N-S and E-W respectively owing to trends of structural evolution of Zaria. Eigbefo (1978) reported a two-phase deformations; one trending in E-W and the other N-S respectively and this might have resulted in the N-S and E-W synclinal structures and the undulated basements mapped in this study. Eigbefo (1978) also noticed that the N-S structural deformation is greater in most places in Zaria than the E-W deformation. This is confirmed by the dipping angle of the E-W trending syncline measured as 19^0-20^0 (Figure 10) which is shown to be less than that of the N-S trending syncline of (Figure 8) which measured as 23^0-26^0.

CONCLUSION

This paper has discussed the use of geophysical tomography in the delineation of the origin of subsurface structures causative to the foundation-based structural instability in some of the low rise and semi high rise building in Samaru area of Zaria, north western Nigeria. High resolution 2D seismic refraction technique and free swell test on foundation soils were used to delineate the foundation depths in the vicinity of three low and semi-high-rise buildings in the area.

The interpreted results show that the area is characterized by active clayey soils at shallow depths, sandy clayey regolith, underlying fractures, dipping layers, undulated basement and synclinal structures at shallow depths. The clayey and highly compressible foundation depths, fractures, undulations of shallow basements and synclinal structures suggest that they are most probably causative to the structural instability of the buildings in Samaru area of Zaria.

The clayey foundation depths most probably resulted from low permeability in the weathered rocks in Zaria windblown particles and a downward movement of clay accumulation thereby forming clayey horizons. The undulated basement structures E-W and the N-S synclinal structural deformations most probably resulted due to E-W and N-S phase deformations respectively. The NW–SE and NE–SW fractures patterns mapped in the study most probably are part of the trans-current movements which resulted to NW–SE and NE–SW fracture pattern in the basement complex.

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